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# DYNAMIC RESPONSES OF A GRAPHITE/EPOXY LAMINATED BEAM TO IMPACT OF ELASTIC SPHERES

by

C.T. Sun and T. Wang

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16. Abstract

Wave propagation in $[90/45/90/-45/90]_{2S}$ and $[0/45/0/-45/0]_{2S}$ laminates of a graphite/epoxy composite due to impact of a steel ball was investigated experimentally and also by using a high order beam finite element. Dynamic strain responses at several locations were obtained using strain gages. The finite element program which incorporated statically determined contact laws was employed to calculate the contact force history as well as the target beam dynamic deformation. The comparison of the finite element solutions with the experimental data indicated that the static contact laws for loading and unloading (developed under this grant) are adequate for the dynamic impact analysis. It was found that for the $[0/45/0/-45/0]_{2S}$ laminate which has a much larger longitudinal bending rigidity, the use of beam finite elements is not suitable and plate finite element should be used instead.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure | page

Figure page

## NOMENCLATURE

| | | |
|---|---|---|
| $A_{ij}$ | = | Laminate stiffness matrix |
| $E_1$ | = | Young's modulus in 1 - (fiber) direction |
| $E_2$ | = | Young's modulus in 2 - (transverse) direction |
| F | = | Contact force |
| $G_{12}$ | = | In-plane shear modulus |
| k | = | Contact coefficient |
| $k_1$ | = | Reloading rigidity |
| $\alpha$ | = | Indentation |
| $\alpha_o$ | = | Permanent indentation |
| $\alpha_m$ | = | Maximum indentation before unloading |
| $\alpha_{cr}$ | = | Critical identation |
| $\mu_{12}$ | = | Poisson's ratio for strain in the 2-direction when stressed in the 1-direction |

# 1. INTRODUCTION

Due to their lack of through-the-thickness reinforcement, laminated fiber composites are susceptible to impact damage. The past effort in the study of FOD (foreign object damage) of composites can be categorized into three aspects, namely, examination of impact damage by testing, wave propagation study, and the search for new impact resistant hybrid composites. Ballistic impact tests on various composites have been conducted by many people [1-4]. Under the sponsorship of NASA Lewis Research Center, a number of aircraft engine companies have carried out full scale testings on impact of composite fan blades [5-7]. Observations made from these tests have led to some understanding of the failure modes and the impact effect on the reduction in the strength of composites.

Some authors have approached the FOD problem by studying stress wave propagation in laminated composites [8-16]. Since the impact resistant properties of composites are not pure material properties but are greatly dependent on the dynamic structural behavior, the understanding of wave propagation in composites due to impact loads is of great importance to the FOD problem.

Recently, attention has been called to the use of super-hybrid composites as a possible solution to the FOD problems [17]. As the search for highly impact-resistant composites continues, the need for better testing procedures and accurate analytical models remains.

Since the impact phenomenon involves both material response at the contact zone and the structural response in the form of stress waves, it is desirable to separate these two. In the past, the classical Hertzian contact law was used to calculate the contact force which was then used as the forcing function in the analysis of the subsequent

dynamic response of the structure after an impact [12, 13, 15]. Recently, Yang and Sun [18] have conducted indentation tests on a graphite/epoxy laminate using spherical indenters and concluded that the classical Hertzian law is not valid. In particular, they found that the permanent deformation at the contact zone is very large and that the unloading path substantially deviates from the loading path. Based upon experimental data, the loading and unloading contact behaviors were modeled in terms of power laws. Since these contact laws were established based on static indentation tests, the validity of these laws in the dynamic impact analysis remains to be verified.

The purpose of this study was to conduct dynamic impact experiments to provide a basis for comparison with the analytical solution using these static contact laws.

## 2. Material Properties and Contact Laws

The graphite/epoxy laminates were provided by NASA Lewis Research Center. Specimens were cut from $[0/45/0/-45/0]_{2s}$ panels of 28 cm x 23 cm x 0.254 cm. When cut in the transverse direction, $[90/45/90/-45/90]_{2s}$ laminate specimens were obtained.

The ply elastic constants $E_1$, $E_2$, $G_{12}$, and $\nu_{12}$ were determined experimentally by an indirect procedure. According to the classical lamination theory, for a symmetric and balanced laminate, we have

$$N_x = A_{11}\,\varepsilon_{xx} + A_{12}\,\varepsilon_{yy} \tag{1}$$

$$N_y = A_{12}\,\varepsilon_{xx} + A_{22}\,\varepsilon_{yy} \tag{2}$$

where $N_x$ and $N_y$ are the in-plane forces in the x- and y- direction, respectively. $\varepsilon_{xx}$ and $\varepsilon_{yy}$ are the normal strains, and $A_{ij}$ are elements of the plate in-plane stiffness matrix [19]. The quantities $A_{ij}$ are functions of the ply elastic constants as well as the fiber orientation.

Simple tension specimens of 2.54 cm width were cut from the large panels into $[0/45/0/-45/0]_{2s}$ and $[90/45/90/-45/90]_{2s}$ laminates. Uniaxial tension tests ($N_x \neq 0$, $N_y = 0$) were then performed and the longitudinal and transverse strains were measured. With the two types of specimens, four equations in the form of Eqs. (1) and (2) were obtained from the experimental data. Since these equations are highly nonlinear in the elastic constants, a numerical iterative procedure was used to find the solution. The results are

$$E_1 = 120 \text{ GPa } (17.5 \times 10^6 \text{ psi})$$
$$E_2 = 7.9 \text{ GPa } (1.15 \times 10^6 \text{ psi}) \tag{3}$$
$$G_{12} = 5.5 \text{ GPa } (0.8 \times 10^6 \text{ psi})$$
$$\nu_{12} = 0.30$$

The contact laws used in this study were obtained by Yang and Sun [18]. For the loading process, the contact force F and the indentation $\alpha$ have the relation

$$F = k\, \alpha^{3/2} \tag{4}$$

where k is a contact coefficient whose value depends on the target material properties and the identer size. For the graphite/epoxy laminate under consideration we have

$$k = 3.36 \times 10^4 \text{ N/mm}^{1.5} \quad (9.7 \times 10^5 \text{ lb/in.}^{1.5}) \tag{5}$$

for the 12.7 mm (0.5) in.) diameter steel identer, and

$$k = 0.94 \times 10^4 \text{ N/mm}^{1.5} \ (5.6 \times 10^5 \text{ lb/in.}^{1.5}) \tag{6}$$

for the 6.35 mm (0.25 in.) diameter indenter.

The unloading process is modeled by the following equation

$$F = F_m \left[\frac{\alpha - \alpha_o}{\alpha_m - \alpha_o}\right]^{2.5} \tag{7}$$

where $F_m$ is the contact force corresponding to the indentation $\alpha_m$ where unloading starts, and $\alpha_o$ is the corresponding depth of the permanent crater. The following formula was suggested by Yang and Sun [18] for computing $\alpha_o$:

$$\alpha_o/\alpha_m = 1 - (\alpha_{cr}/\alpha_m)^{2/5} \quad (8)$$

with

$$\alpha_o = 0 \text{ if } \alpha_m \leq \alpha_{cr} \quad (9)$$

In Eq. (8), the parameter $\alpha_{cr}$ is constant for both sizes of indenter. For this graphite/epoxy,

$$\alpha_{cr} = 8.0 \times 10^{-2} \text{ mm} \quad (10)$$

The reloading behavior is modeled by

$$F = k_1(\alpha - \alpha_o)^{3/2} \quad (11)$$

in which

$$k_1 = F_m/(\alpha_m - \alpha_o)^{3/2} \quad (12)$$

is the reloading rigidity. This formula has been experimentally verified by Yang and Sun [18].

A higher order beam finite element with six degrees of freedom was used in conjunction with the contact laws for the dynamic impact analysis. A complete listing of this program can be found in [20]. This program is able to calculate the transient contact force, the dynamic deformation, and stresses in the beam under any impact condition. For all the numerical solutions, the beam was modeled with finite elements of size 6.25 mm and a $0.2 \times 10^{-6}$ sec. time increment was chosen for the time integration. This finite element size and time increment have been tested and found to yield convergent solutions.

## 3. Experimental Procedures

The schematic diagram for the experimental set-up is shown in Fig. 1. A pendulum with a steel ball of 12.7 mm diameter was used as the impactor for low velocity impact (below 5 m/sec), and an air gun was used to shoot a 6.35 mm diameter steel ball for high velocity impacts. By adjusting the pressure of the compressed air in the chamber of the air gun the velocity of the projectile ranges from 20 m/sec to 100 m/sec.

Two light emitting diodes (LED) and two photo detectors were used to find the velocity of the projectile. When the projectile interrupts the first light beam, a pulse is generated to start the time counter. Once the projectile cuts the second light beam, another pulse is generated to stop the counter. The velocity of the projectile is obtained by dividing the distance between the two LED's by the time registered on the counter.

Two boundary conditions were realized in the impact experiments, namely, clamped-clamped and free-free conditions. For the clamped-clamped condition, the specimen was tightly gripped to a massive stand while in the case of free-free end condition, the specimen was hung on two thin strings. Strain gages were mounted on the specimen at various locations. One gage was placed exactly on the back side of the impact point for triggering the oscilloscope which recorded the strain signals from other gages. The strain gages (EA-13-062 AQ 350) were marketed by Micro Measurement Co. and Eastman 910 was used as the bonding glue. Signals from the gages were amplified by a 3A9 Textronix amplifier and displayed on the screen of the oscilloscope.

All test specimens were approximately 25.4 mm (1 in.) wide. The length of the beam specimens ranged from 177.8 mm to 381 mm.

## 4. Results and Discussions

Daniel et al [14] have concluded from their transverse impact experiments that the in-plane membrane deformation is negligible. To verify this in our case, a series of tests were conducted with two strain gages mounted on the opposite faces of the laminated beam to record the longitudinal normal strain histories at a certain location. From the results presented in Figs. 2 and 3, it can be seen that the strains on the opposite sides of the beam have the same magnitudes but opposite signs. This indicates that the deformation is dominated by bending, i.e., the impact-induced motion is predominantly a flexural wave.

### 4.1 $[90/45/90/-45/90]_{2s}$

Figure 4 shows the typical dynamic contact force, the displacement of the impacting ball and the displacement of the beam at the impact point predicted by the finite element program along with the contact laws. The difference between the ball and beam displacements is the indentation. The multiple impacts are the results of waves reflected from the clamped ends.

In Figs. 5-7, the longitudinal surface strains at different locations on a clamped-clamped $[90/45/90/-45/90]_{2s}$ laminate subjected to impact of a 12.7 mm diameter steel ball are presented. The impact velocity was 3.16 m/sec. The finite element solutions seem to agree very well with the experimental data at the initial period after the wave arrives. The agreement is especially good at points closer to the impact point. After the initial wave train passes the gage

location, discrepancies between the finite element solutions and experimental results are noted.

Initially, such discrepancies were thought to be originated from the numerical instability in the finite element program. However, a study on the numerical stability indicated that the finite elements had already converged. This led to the re-examination of the boundary conditions. It was suggested that the clamped end condition as modeled by the finite elements was not actually realized in the experiment and part of the wave might have penetrated into the grips and was reflected totally as predicted by the finite element solution which exhibits a strong oscillatory behavior due to wave reflections. To verify this point, a free-free laminated beam (2.82 mm x 27.9 mm x 177.8 mm) was used. The dynamic strain history at 38.1 mm from the impact point is shown in Fig. 8. Excellent agreement between the finite element solution and the experimental data up to 400 $\mu$ sec. is noted.

More experiments with a free-free beam were then conducted. This beam was substantially longer (381 mm) than the previous one (177.8 mm). The experimentally obtained strain histories at three different locations are shown in Figs. 9-11. It is evident that the experimental results also show a pronounced oscillatory behavior as predicted by the finite element solutions, although of a lesser magnitude. This smaller strain magnitude at the later time could be due to material damping which has not been taken into account in the finite element solution. It is also noted that the wave predicted by the finite element solution travels at a slightly lower velocity than the measured value. This could be due to the fact that the displacement-formulated finite element tends to be stiffer than the actual structure.

The results for higher impact velocities (in the range of 30 m/sec) are shown in Figs. 12-15. From Fig. 12, it is noted that at higher impact velocities, multiple impacts exist no more. The basic characteristics are similar to those at lower impact velocities.

## 4.2 $[0/45/0/-45/0]_{2s}$ Graphite/Epoxy Beam

Unlike the $[90/45/90/-45/90]_{2s}$ laminated beam, the $[0/45/0/-45/0]_{2s}$ laminated beam has much greater bending rigidity in the longitudinal direction. It would take longer time for waves to travel across the width of the specimen. As a result, the use of beam finite element to model the specimen (25.4 mm wide) may not be adequate.

For this type of laminate, the specimen was clamped at both ends during the impact test. The impact force was calculated by using the finite element program with the result shown in Figs. 16-17 for low and high impact velocities, respectively.

Figure 18 shows the strain response at a location 38.1 mm from the impact point on a beam of dimensions 2.72 mm x 27.7 mm x 228.6 mm subjected to impact of a 12.7 mm diameter steel ball. The impact velocity is 3.16 m/sec. Figures 19-21 present the strain histories at three different locations on a beam of similar dimensions under the same impact condition. From these results, it is clear that, although the finite element solutions yield the same trend, they predict higher peak strain magnitudes than the experimental data.

The results for higher impact velocities are shown in Figs. 22-25. Two phenomena are readily observed. First, the wave is reflected and returns much faster due to the higher bending rigidity of the beam.

Second, there seems to be a wave of significant magnitude traveling in the width-direction that is reflected by the free edges and returns to interact with the main flexural wave in the longitudinal direction. The hump in the strain curve for the point located at 38.1 mm from the impact point (at 50 $\mu$ sec after impact) could be attributed to the arrival of the transverse flexural wave. Indeed, if plate finite elements are used, the analytical solution also exhibits such behavior. The plate finite element solution will be discussed in a forthcoming report.

### 4.3 Span Effect

To further study the phenomenon of the longitudinal reflected waves, several experiments with specimens of different lengths were conducted. Fig. 26 shows the experimental results for two $[90/45/90/-45/90]_{2s}$ laminated beams of 203.2 mm and 355.6 mm in length, respectively. These beams were clamped at both ends and were subjected to impact of a 6.35 mm steel ball at a velocity of 30 m/sec. It is evident that initially before the reflected wave arrives, the strains in these two beams are identical.

Fig. 27 shows the experimental results for two $[90/45/90/-45/90]_{2s}$ laminated beam subjected to impact at a lower velocity (3.16 m/sec). The results for the $[0/45/0/-45/0]_{2s}$ laminated beam are presented in Fig. 28. Again, the same conclusion can be drawn.

## 5. Conclusions

Experiments were conducted to study flexural wave propagation in a graphite/epoxy lamianted composite. Both $[90/45/90/-45/90]_{2s}$ and $[0/45/0/-45/0]_{2s}$ laminates were used in these experiments. Dynamic strain responses at various locations of a steel ball impact were measured by strain gages. The impact velocity considered ranges from 3 m/sec to about 37 m/sec. A finite element program which incorporated statically measured contact laws was employed to calculate the dynamic impact responses. The experimental results were compared with the finite element solutions.

The result of this study indicates that the statically determined contact laws are adequate for the dynamic impact analysis. The beam finite element is more suitable for modeling the $[90/45/90/-45/90]_{2s}$ laminate due to its higher transverse bending rigidity. The $[0/45/0/-45/0]_{2s}$ laminate, on the other hand, exhibits strong plate bending effects even for a large aspect ratio. For more accurate analytical results, plate finite elements should be used.

## Acknowledgment

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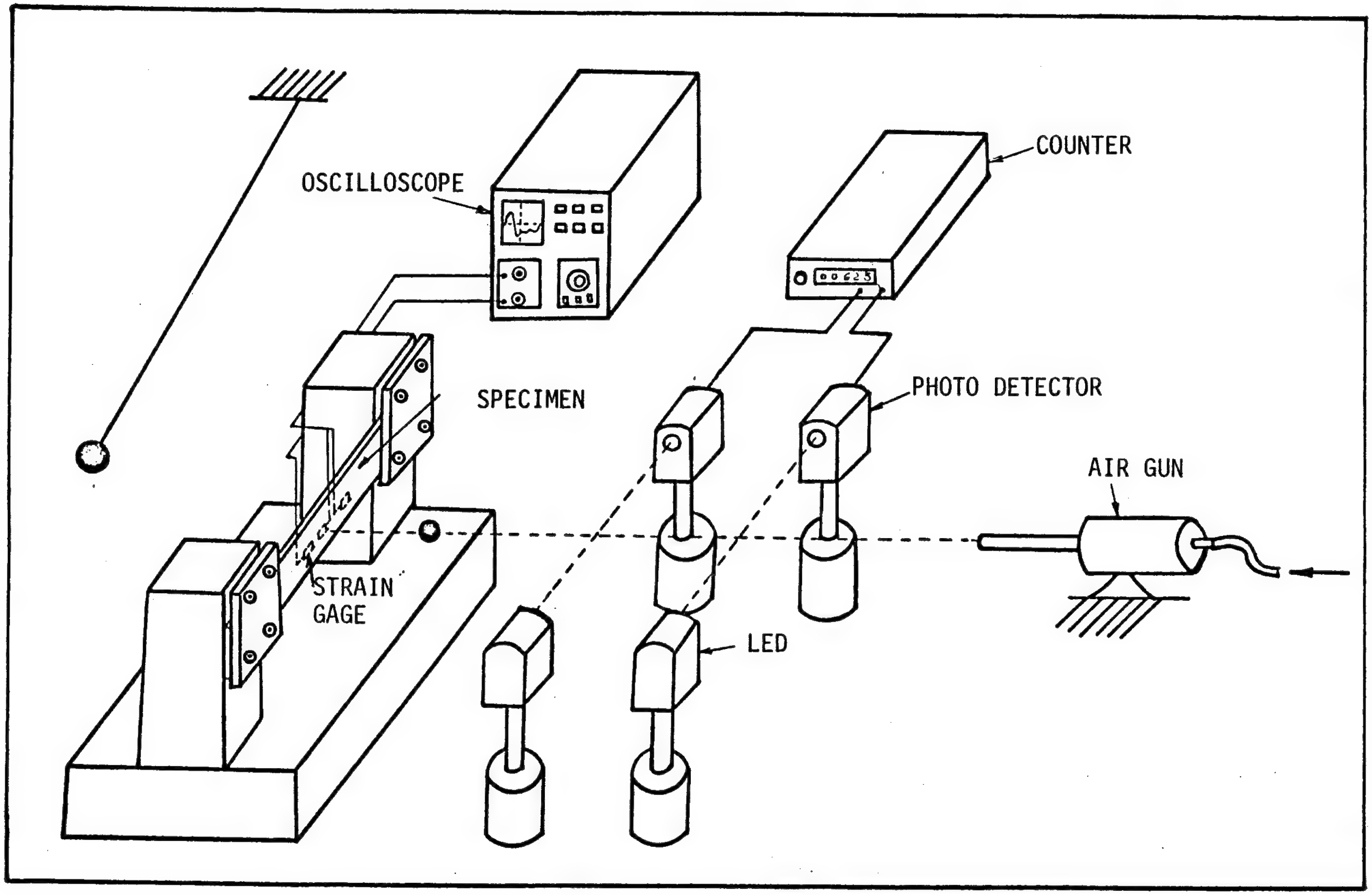


Fig. 1 Schematic Diagram of experimental apparatus.

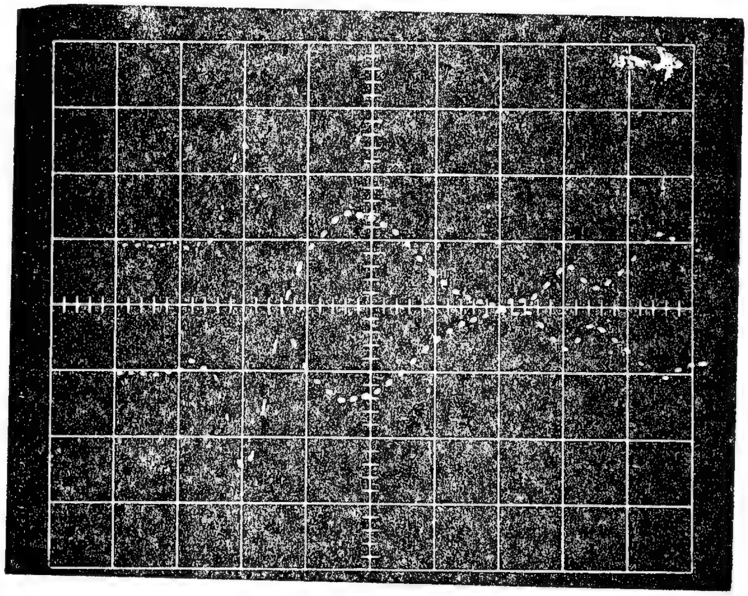

Fig. 2 Strain-gage signals on opposite faces at 38.1 mm from the impact point on the $[90/45/90/-45/90]_{2s}$ beam (2.62 mm x 27.74 mm x 228.6 mm) impacted with a 6.35 mm diameter steel ball at 31.46 m/sec.

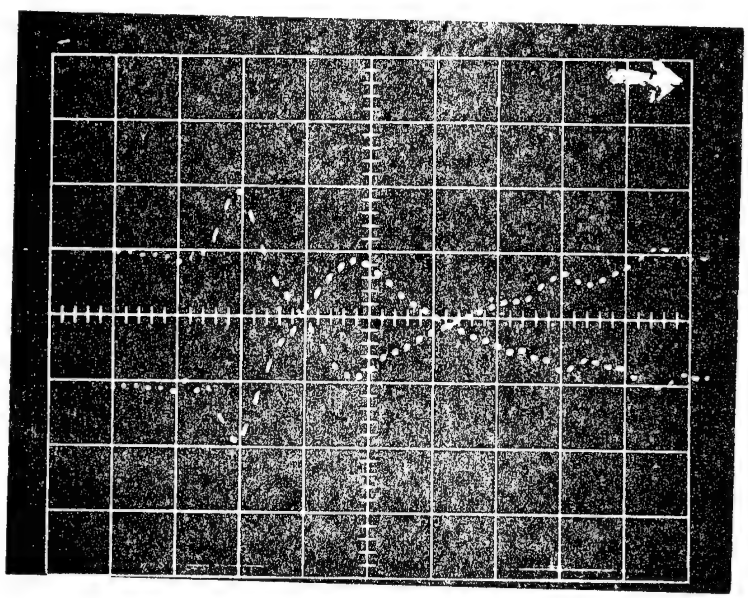

Fig. 3 Strain-gage signals on opposite faces at 38.1 mm from the impact point on the $[90/45/90/-45/90]2_s$ beam (2.59 mm x 27.91 mm x 228.6 mm) impacted with a 6.35 mm diameter steel ball at 46.65 m/sec.

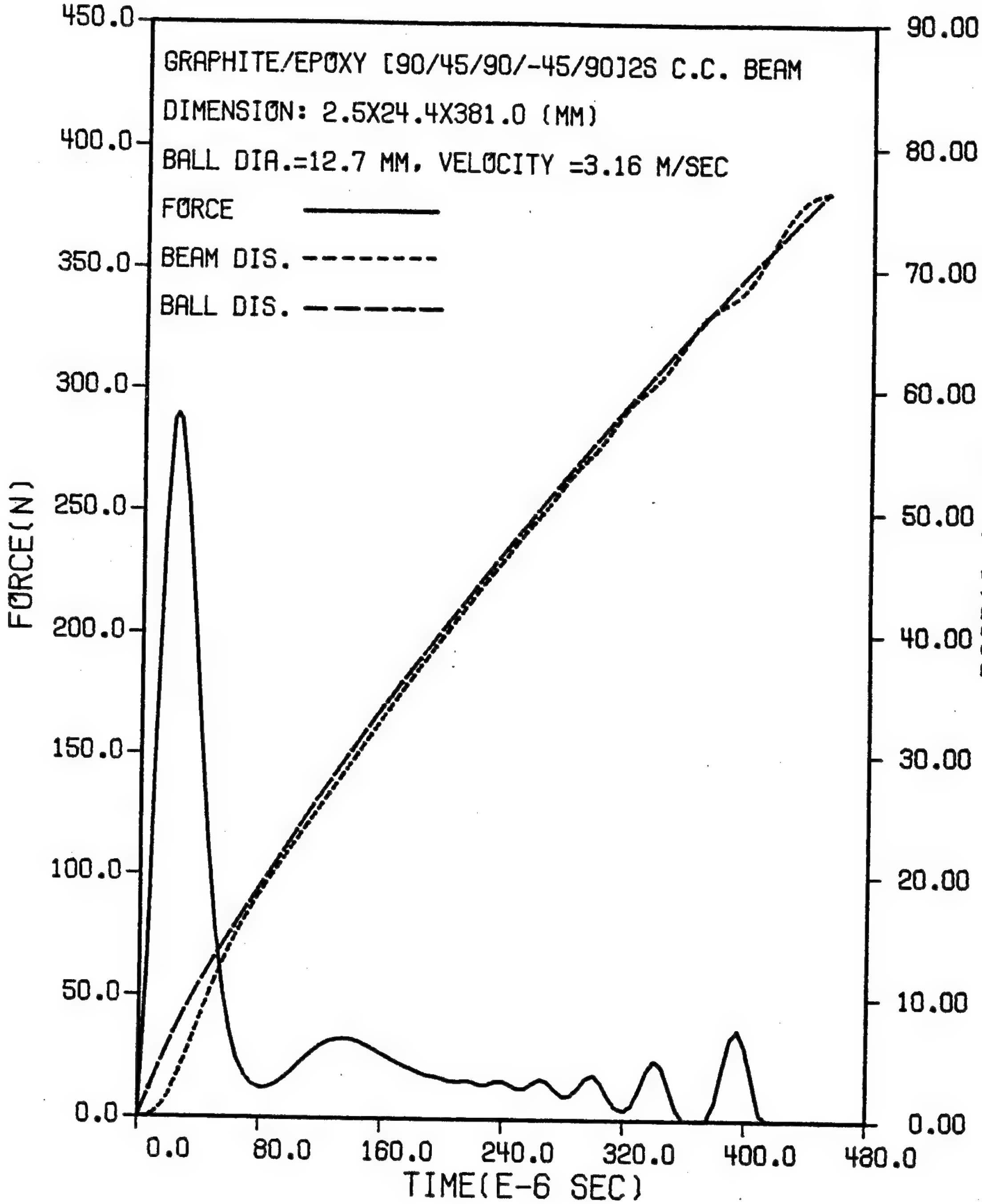


Fig. 4 Contact force and displacements of beam and ball for impact velocity 3.16 m/sec.

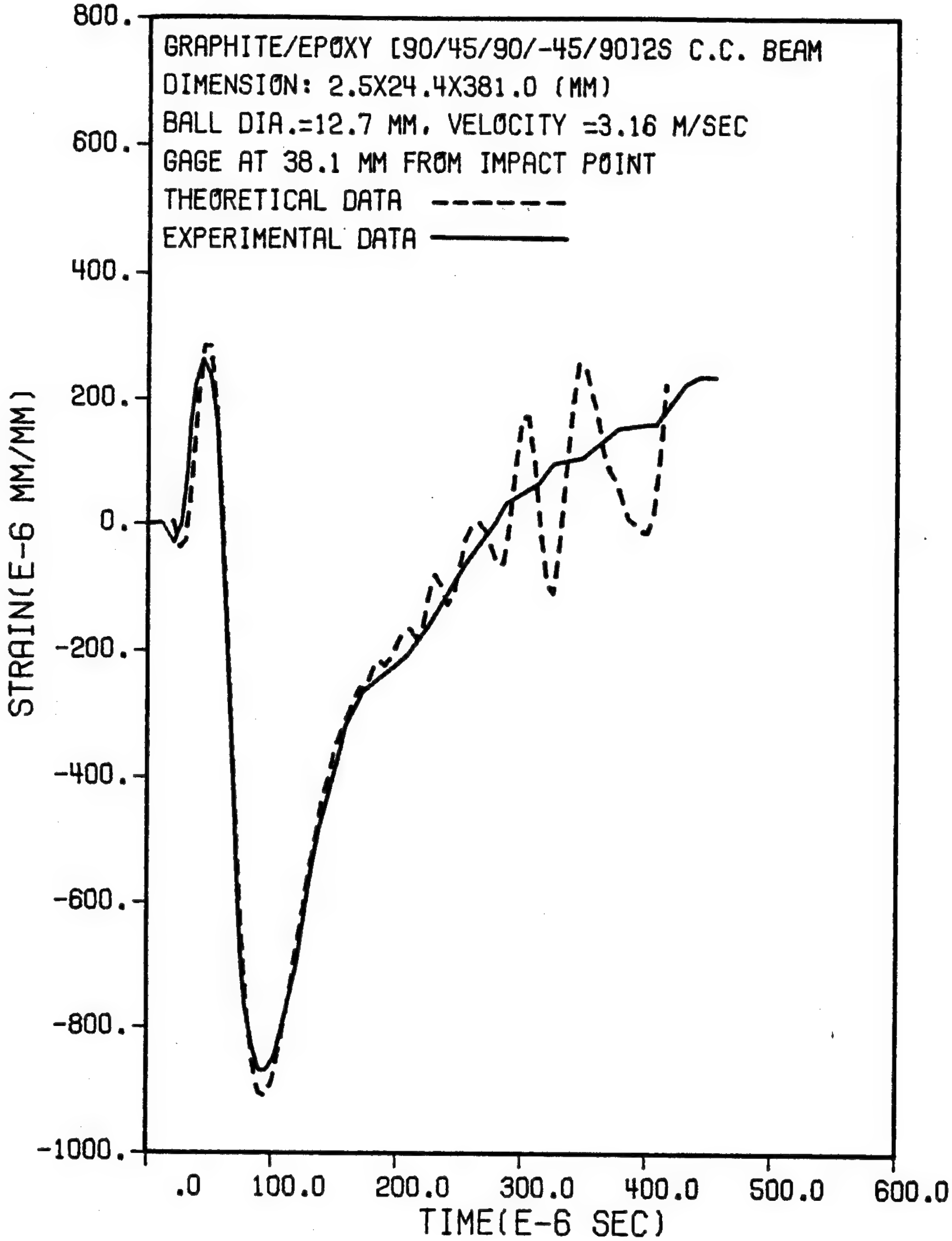


Fig. 5 Experimental and theoretical strain responses for a clamped-clamped $[90/45/90/-45/90]_{2s}$ beam at 38.1 mm from the impact point.

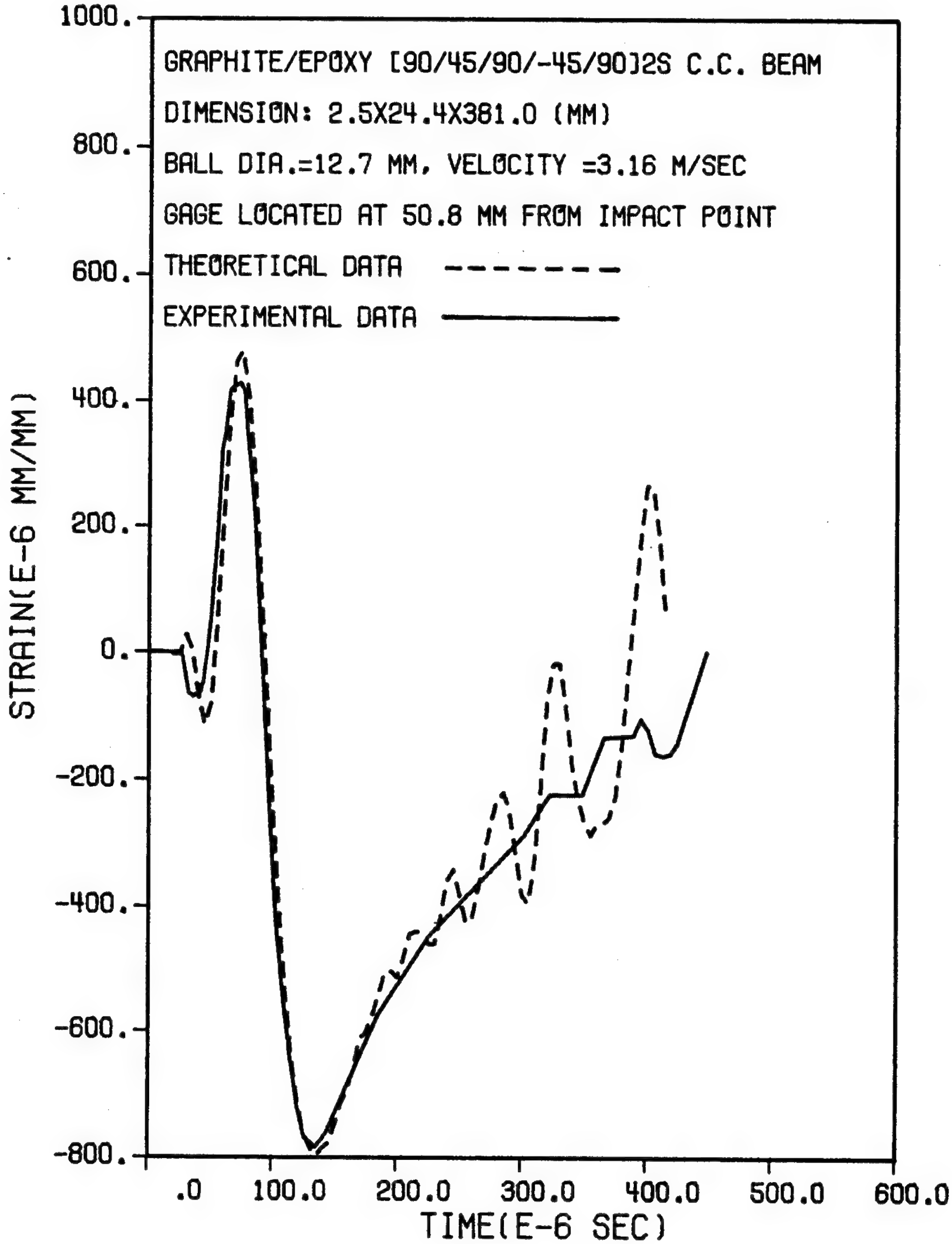


Fig. 6 Experimental and theoretical strain responses for a clamped-clamped $[90/45/90/-45/90]_{2s}$ beam at 50.8 mm from the impact point.

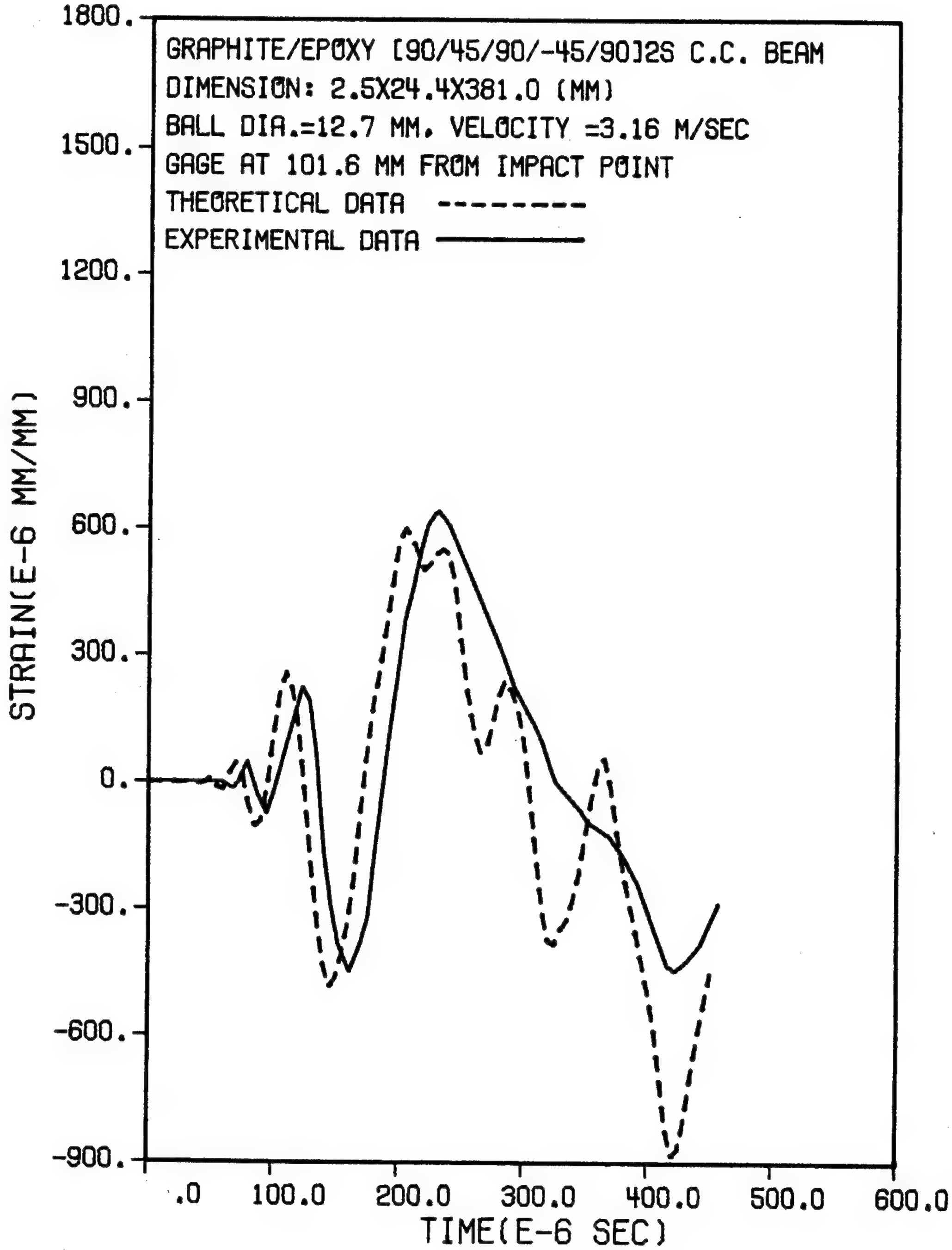


Fig. 7 Experimental and theoretical strain responses for a clamped-clamped $[90/45/90/-45/90]_{2s}$ beam at 101.6 mm from the impact point.

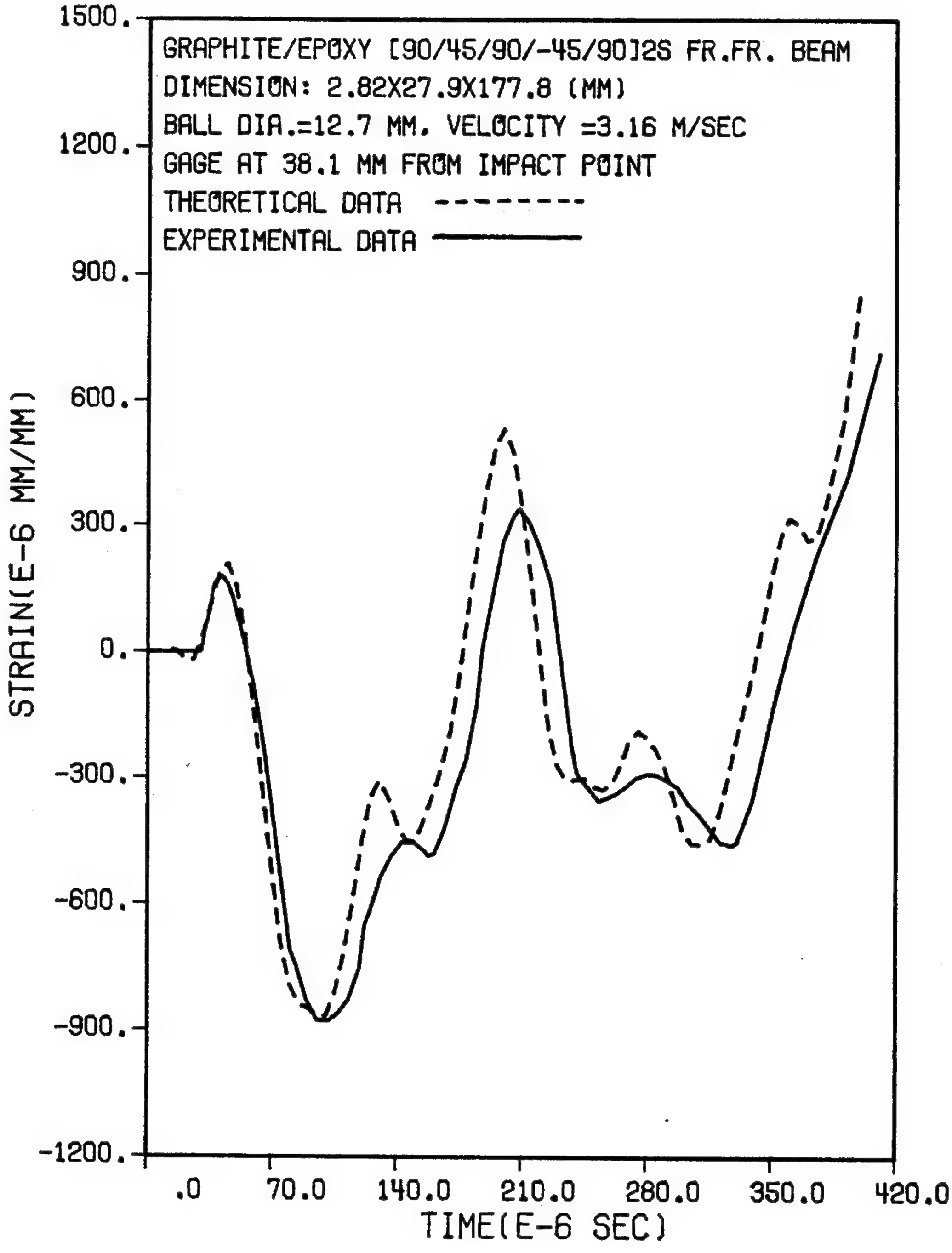


Fig. 8 Experimental and theoretical strain responses for a free-free $[90/45/90/-45/90]_{2s}$ beam at 38.1 mm from the impact point.

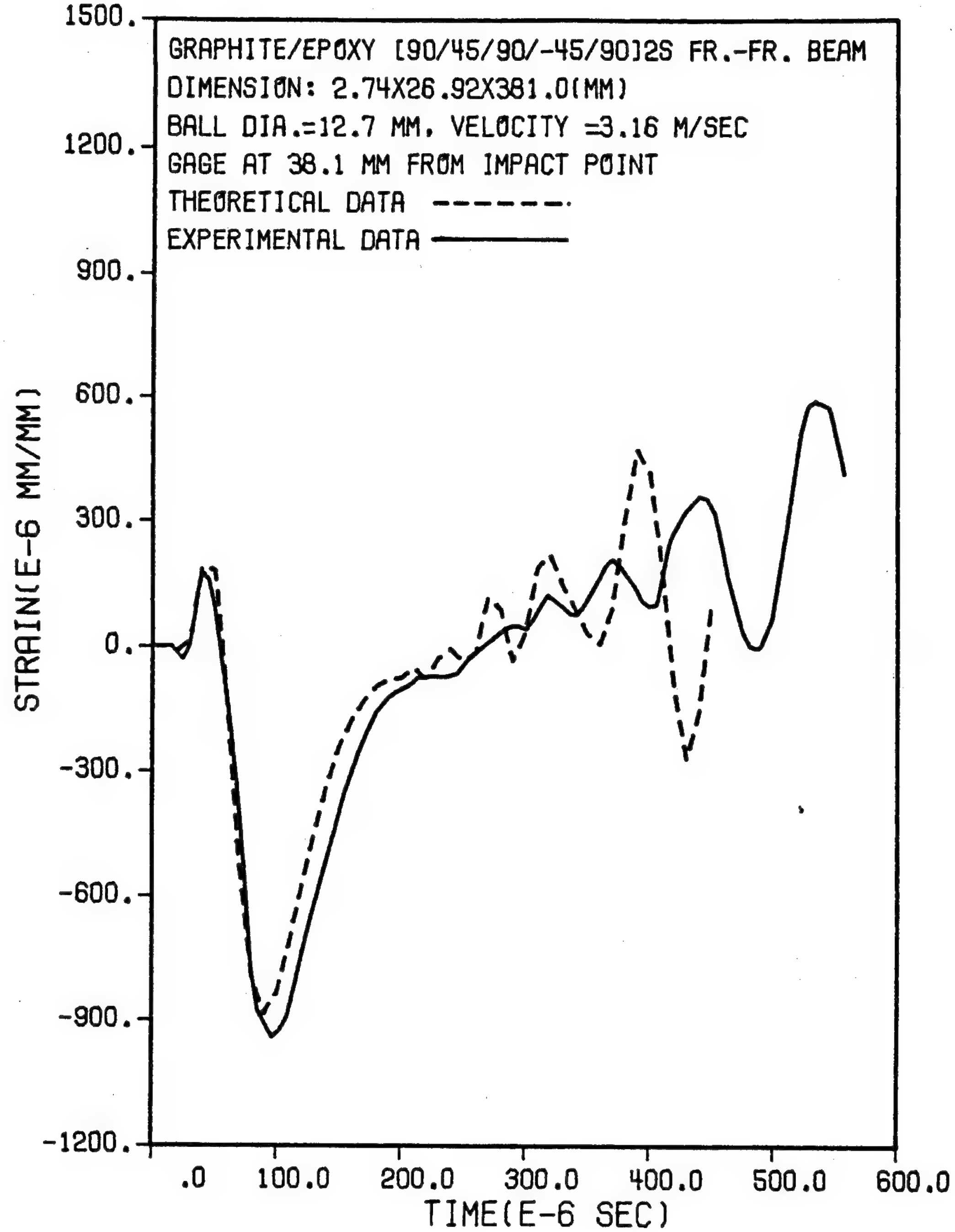


Fig. 9 Experimental and theoretical strain responses for a free-free $[90/45/90/-45/90]_{2s}$ beam at 38.1 mm from the impact point.

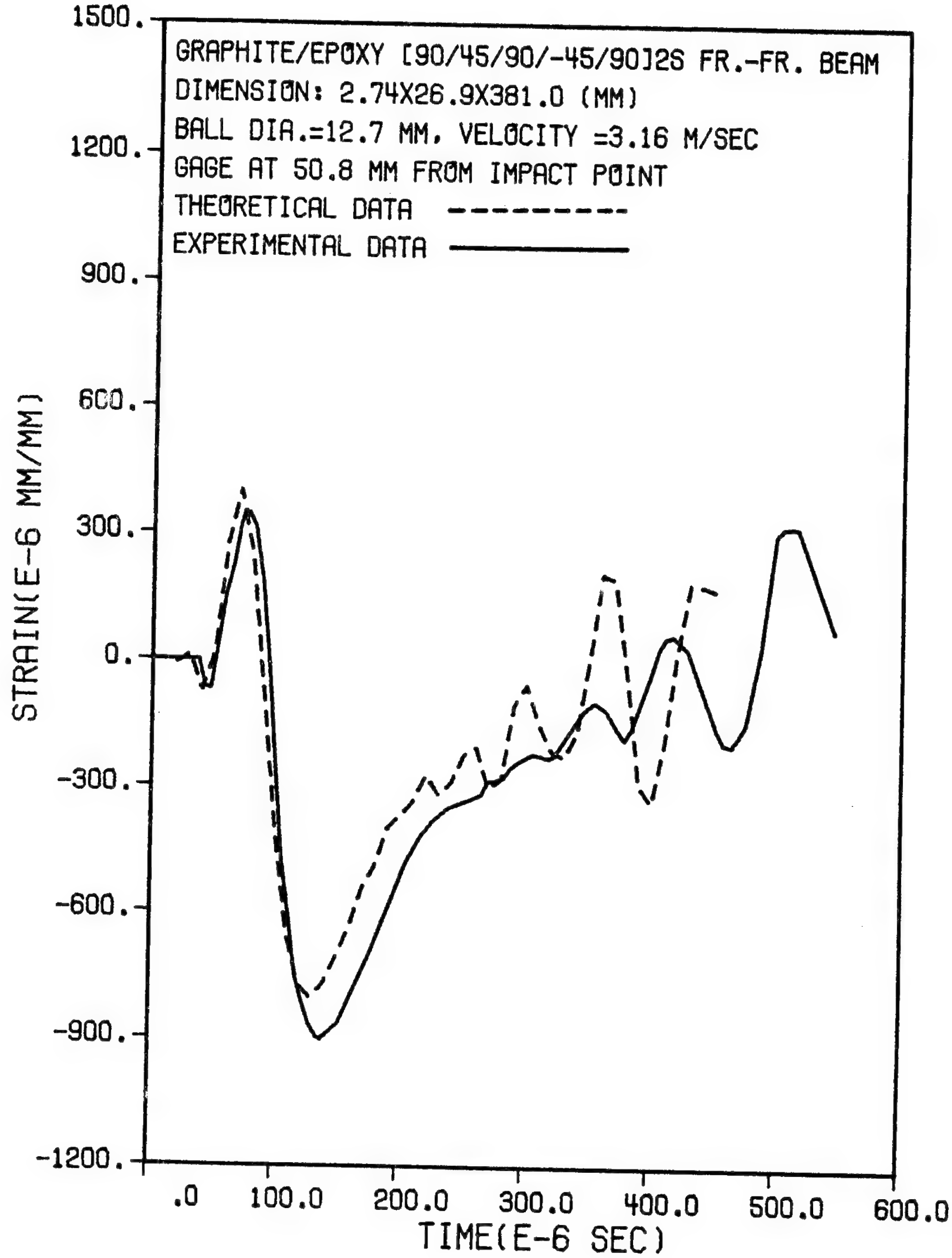


Fig. 10 Experimental and theoretical strain responses for a free-free $[90/45/90/-45/90]_{2s}$ beam at 50.8 mm from the impact point.

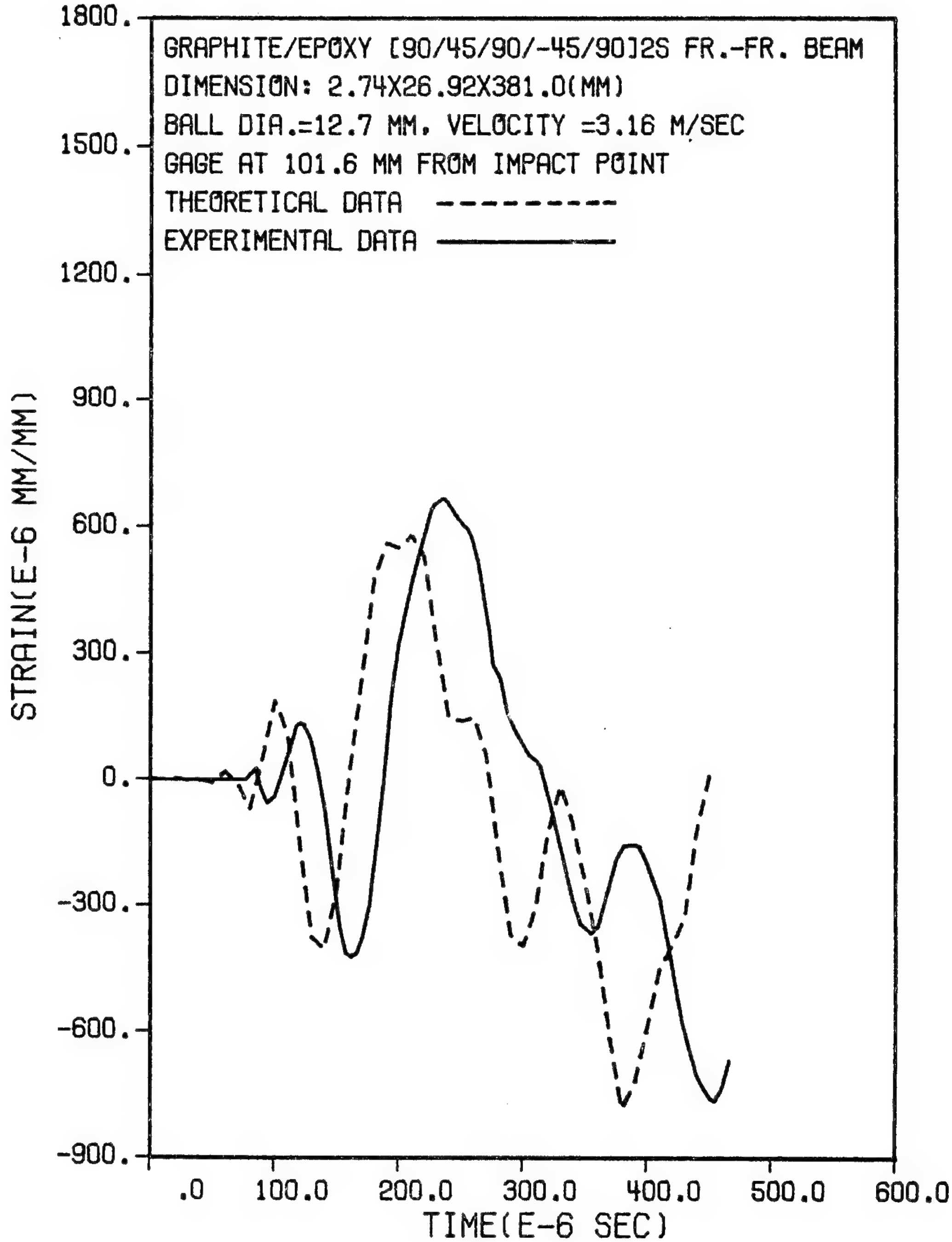


Fig. 11 Experimental and theoretical strain responses for a free-free $[90/45/90/-45/90]_{2s}$ beam at 101.6 mm from the impact point.

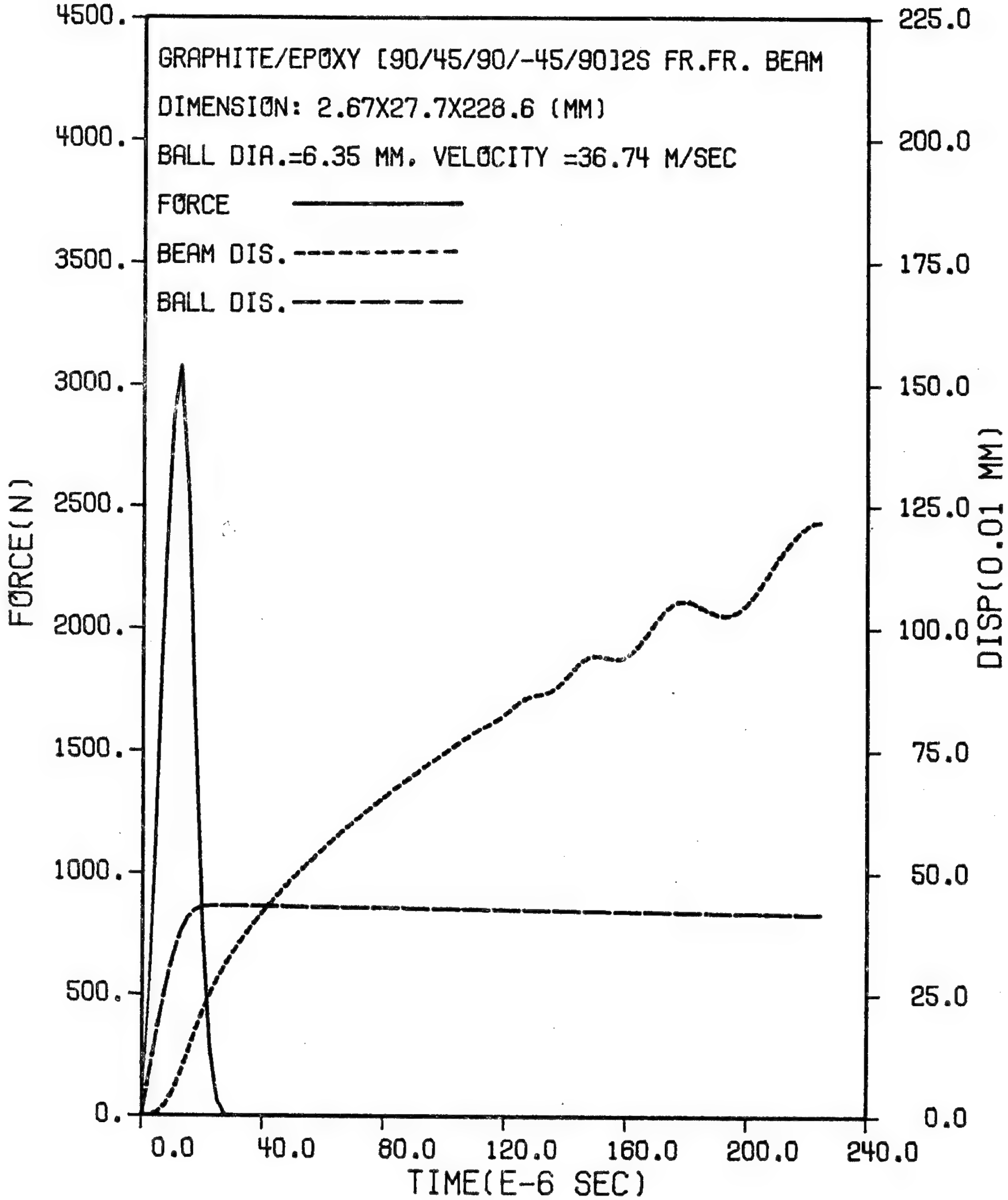


Fig. 12 Contact force and displacements of beam and ball for impact velocity 36.74 m/sec.

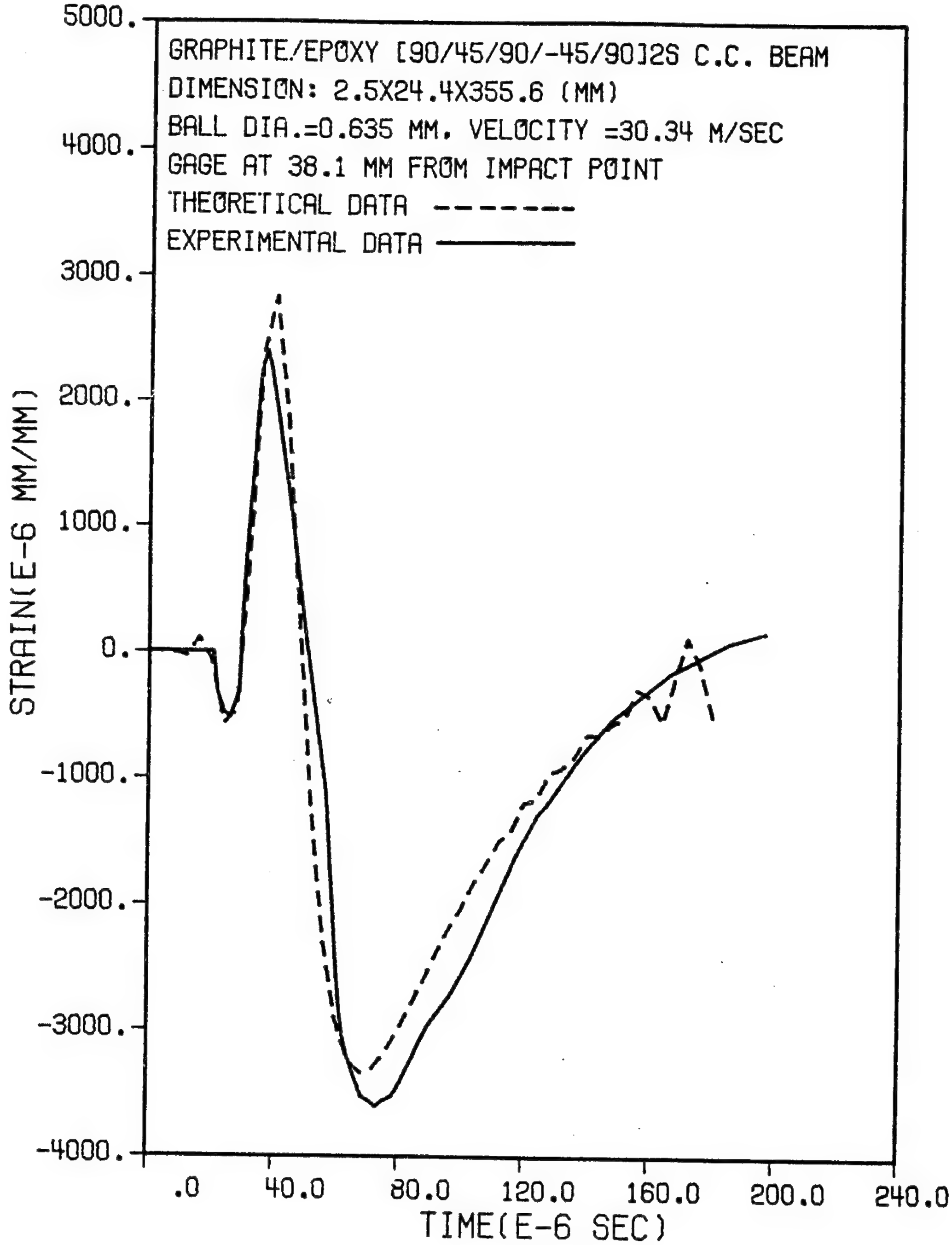


Fig. 13 Experimental and theoretical strain responses for a clamped-clamped $[90/45/90/-45/90]_{2s}$ beam at 38.1 mm from the impact point.

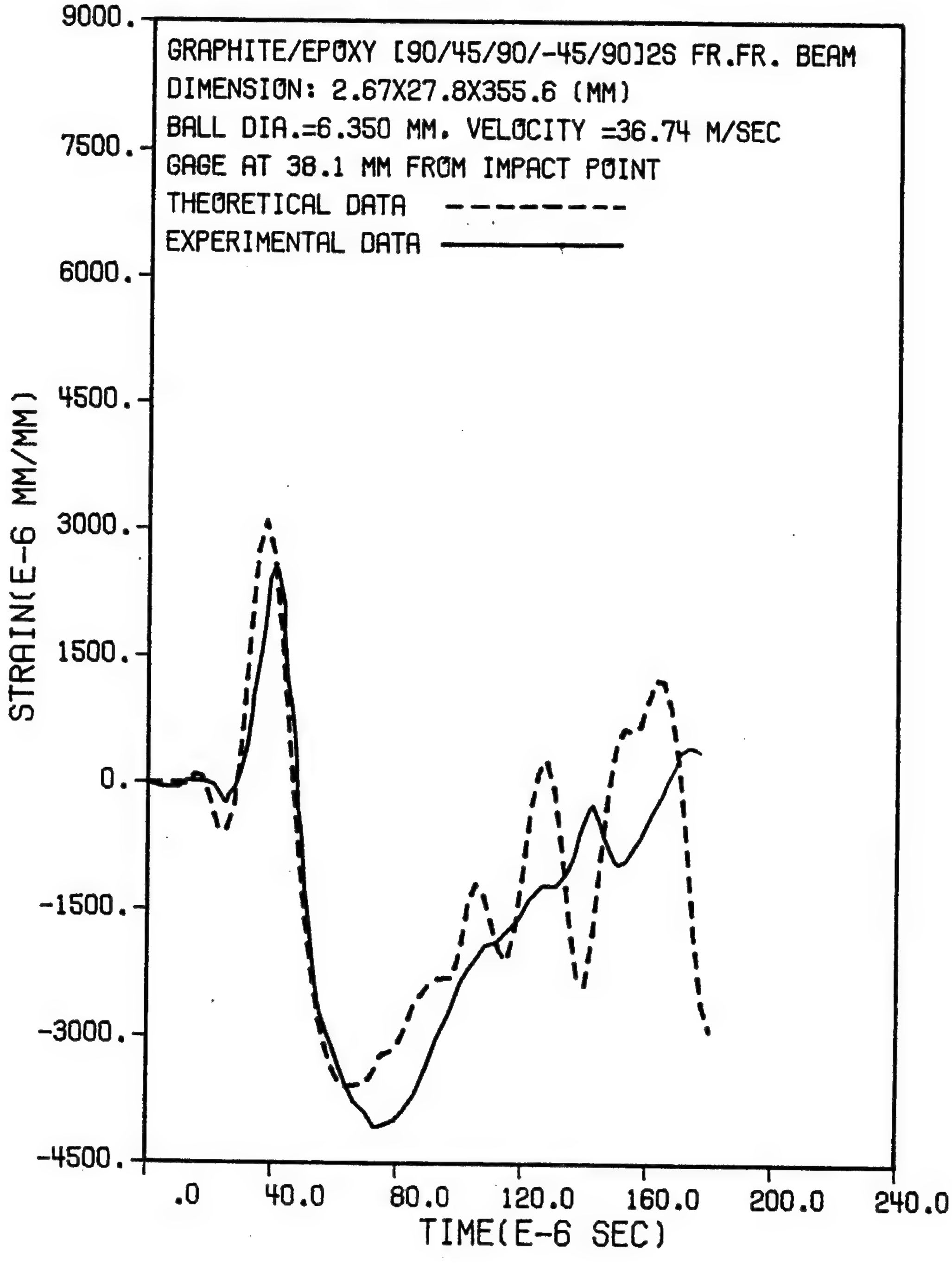


Fig. 14 Experimental and theoretical strain responses for a free-free $[90/45/90/-45/90]_{2s}$ beam at 38.1 mm from the impact point.

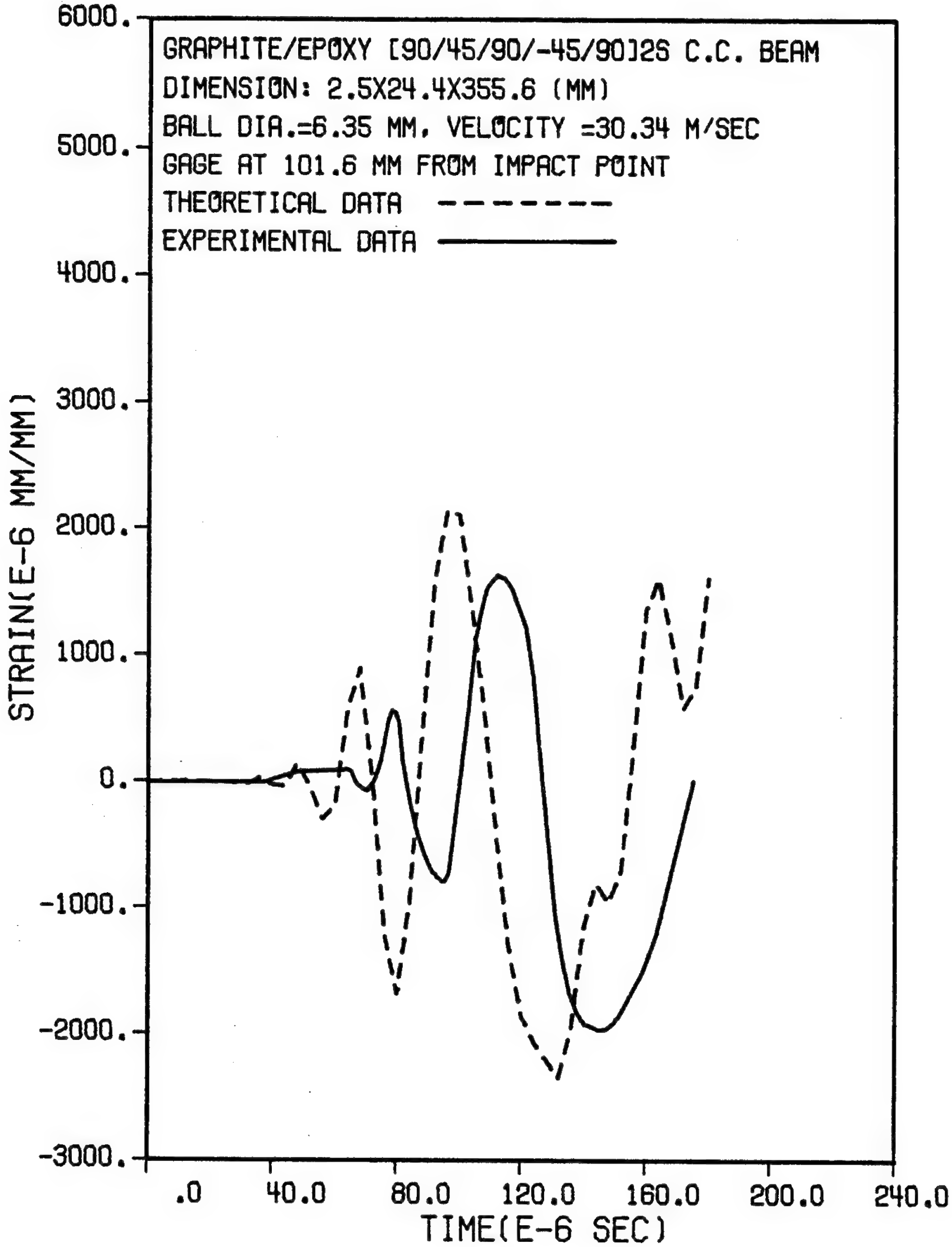


Fig. 15 Experimental and theoretical strain responses for a clamped-clamped $[90/45/90/-45/90]_{2s}$ beam at 101.6 mm from the impact point.

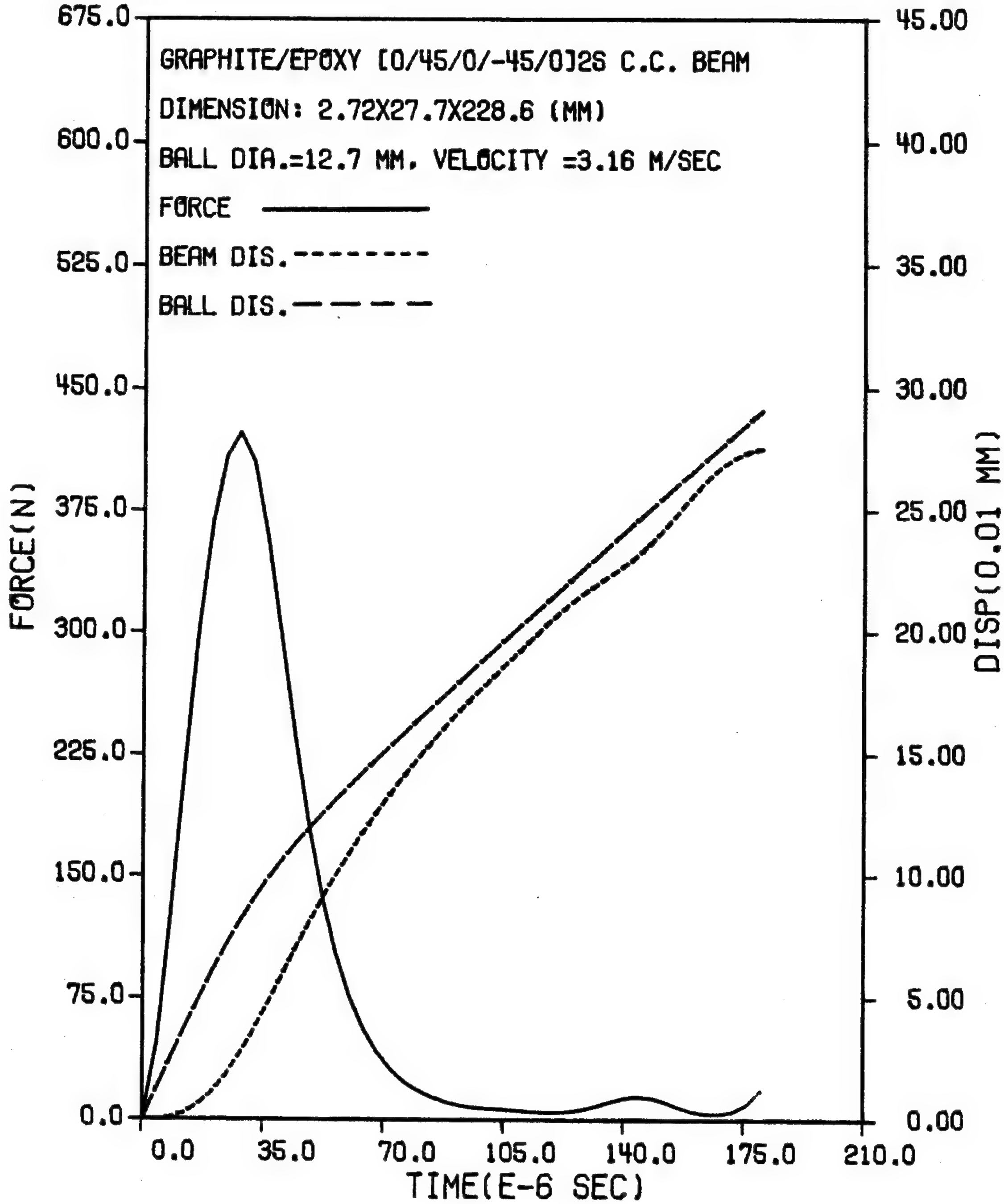


Fig. 16 Contact force and displacements of beam and ball for impact velocity 3.16 m/sec.

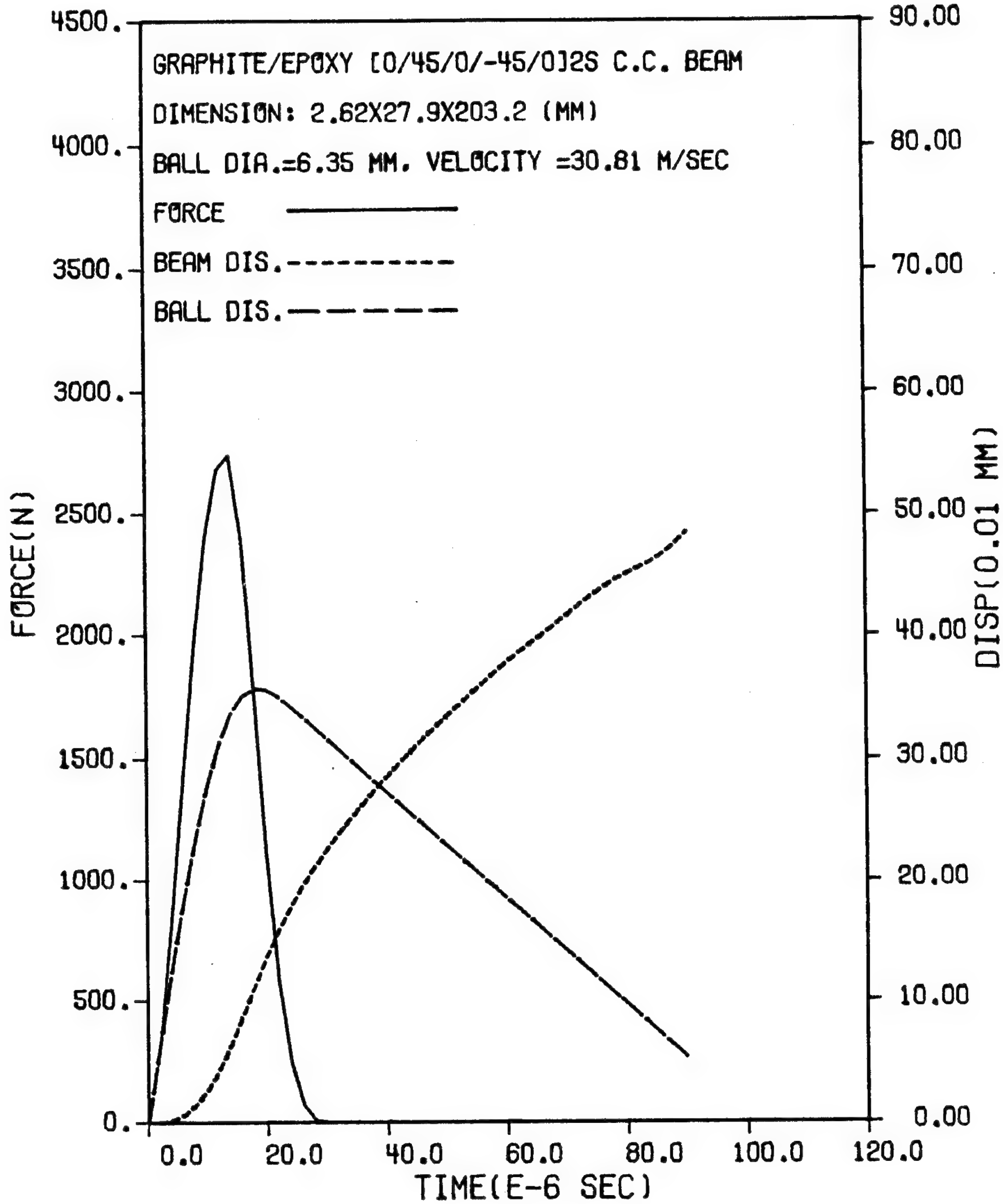


Fig. 17 Contact force and displacements of beam and ball for impact velocity 30.81 m/sec.

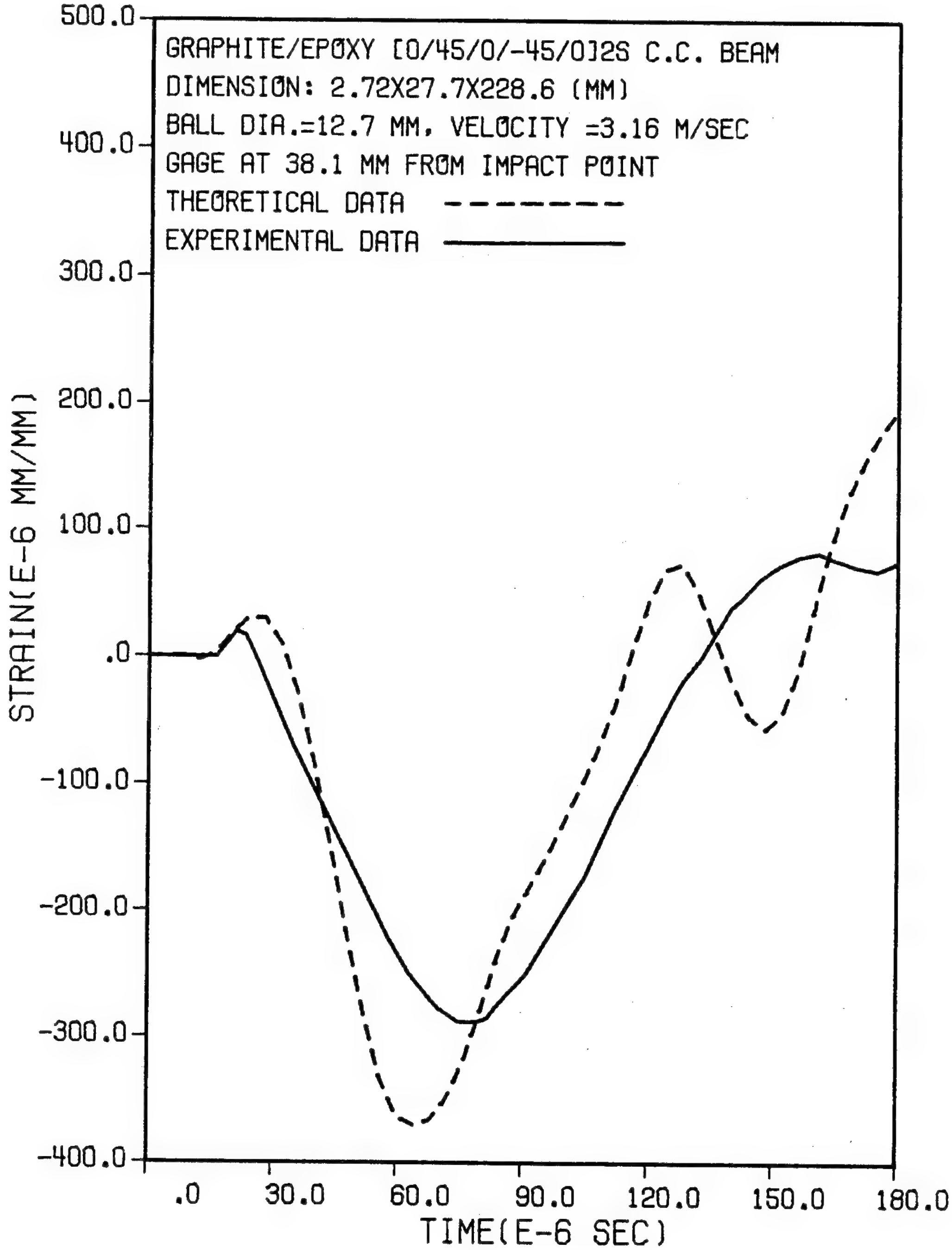


Fig. 18 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 38.1 mm from the impact point.

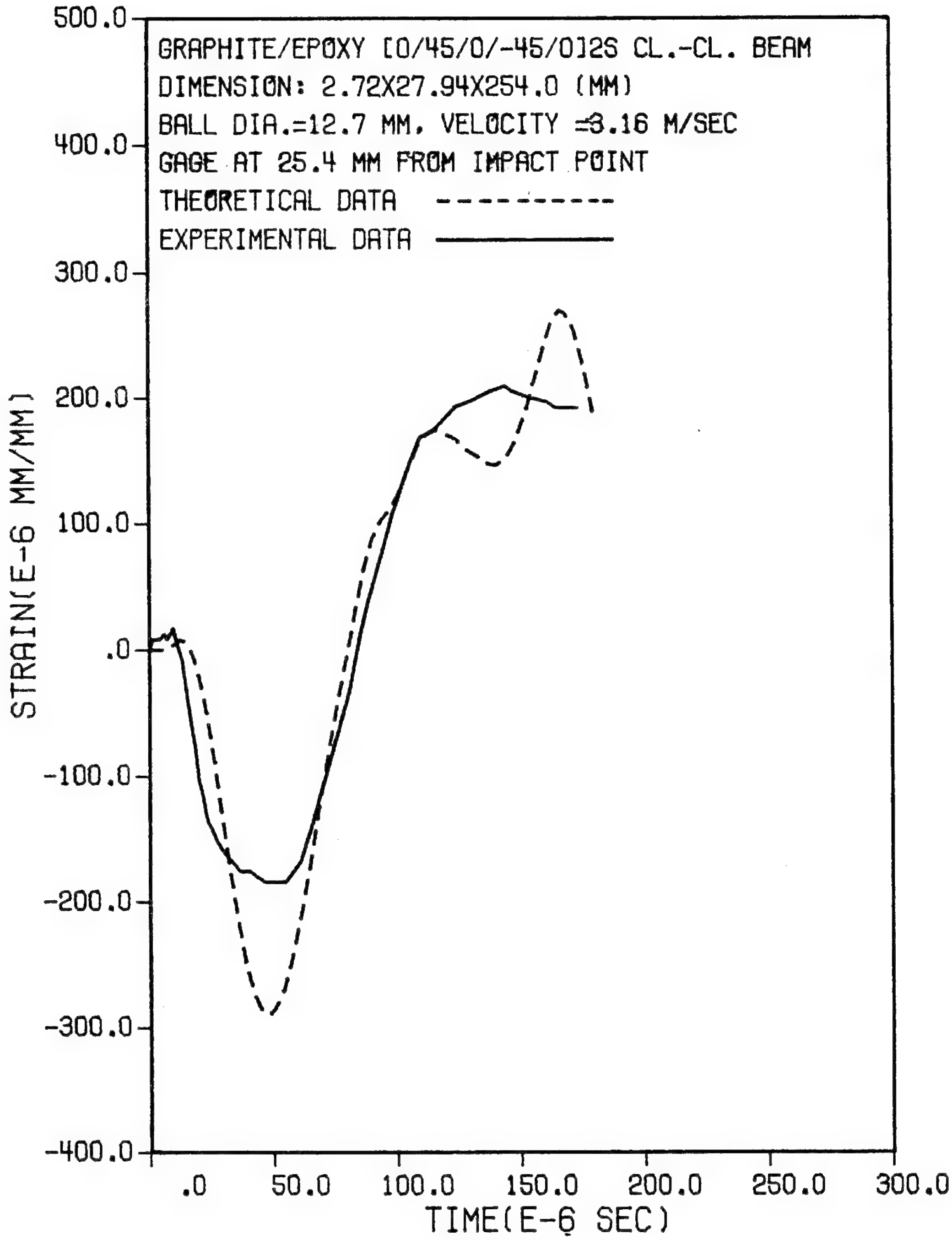


Fig. 19 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 25.4 mm from the impact point.

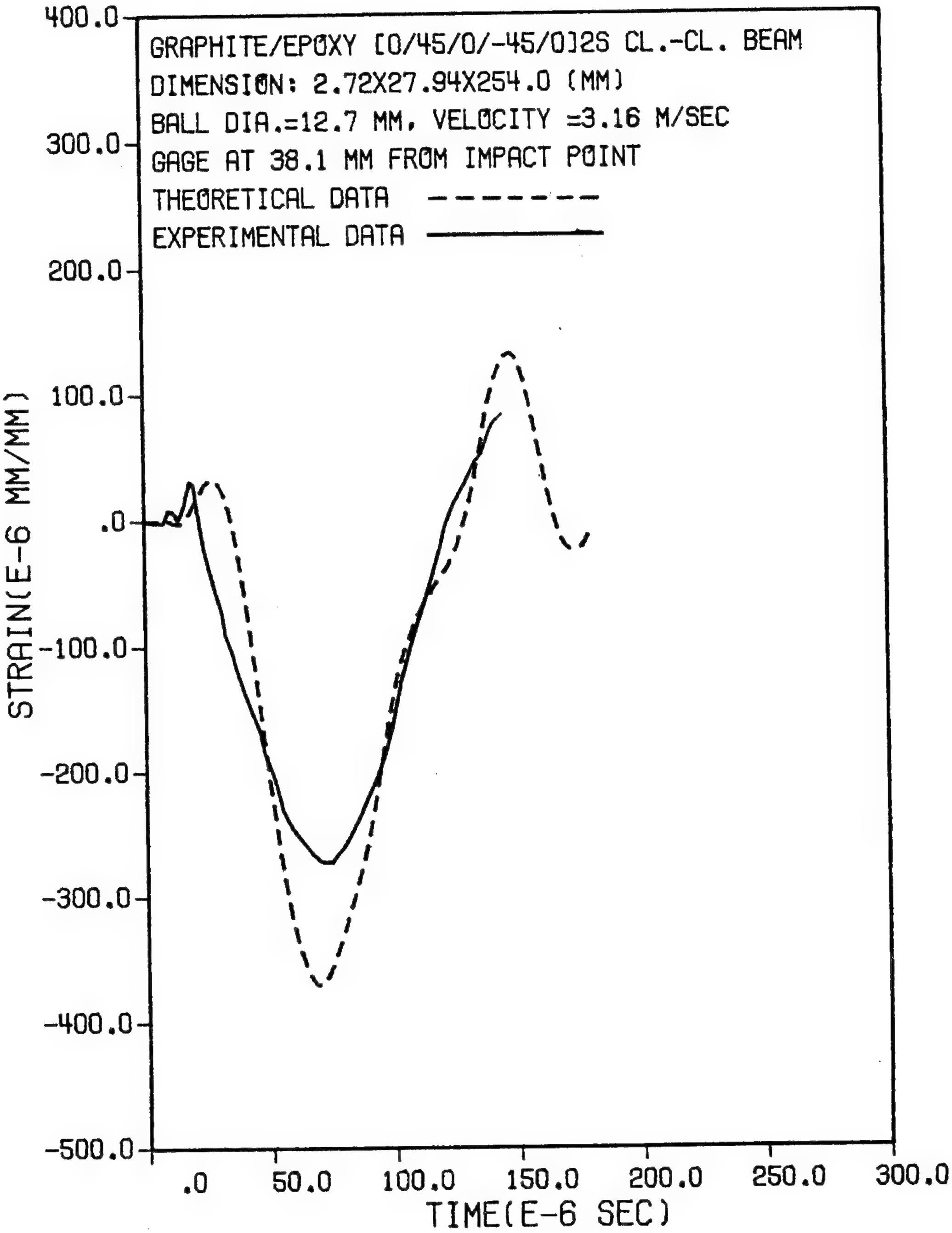


Fig. 20 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 38.1 mm from the impact point.

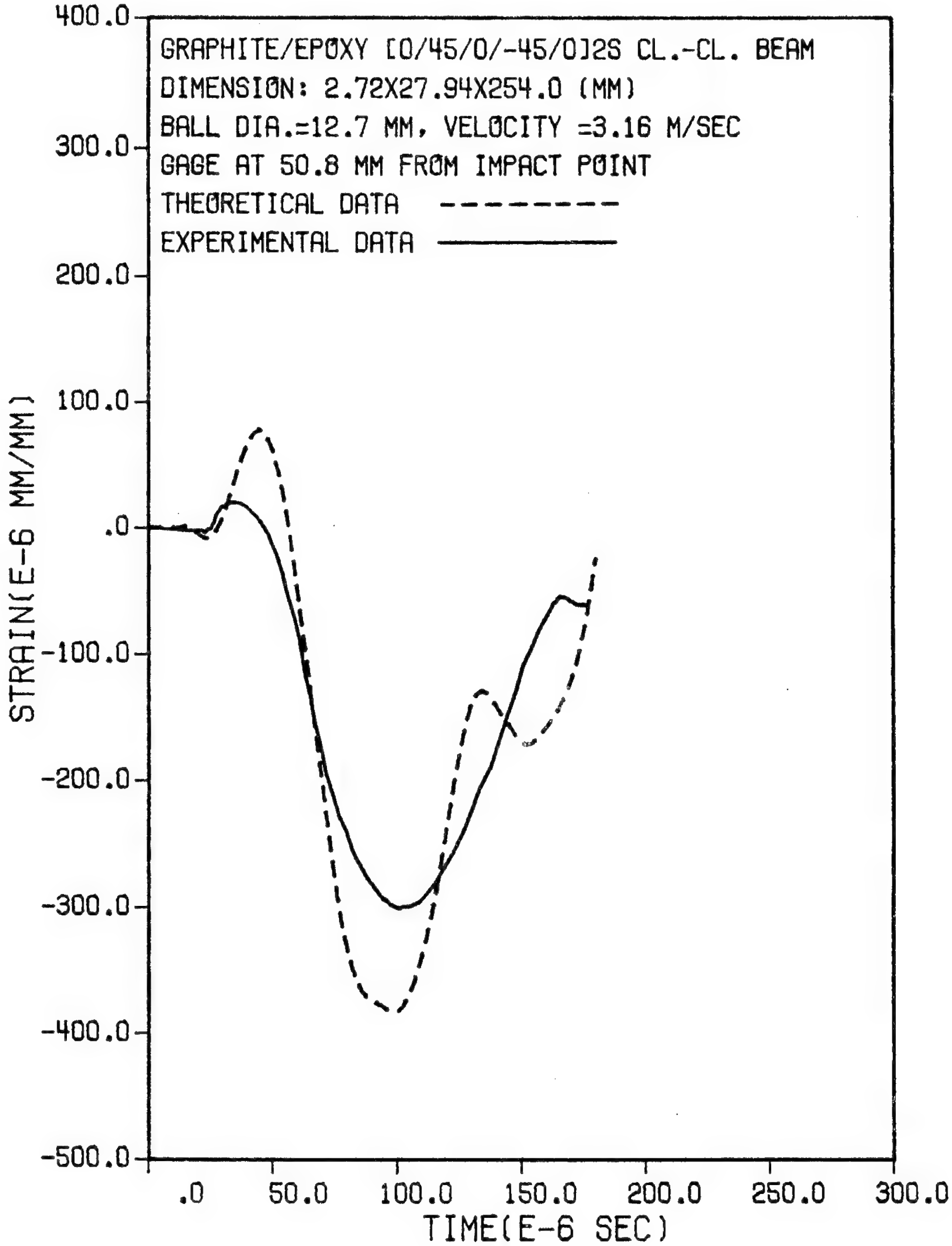


Fig. 21 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 50.8 mm from the impact point.

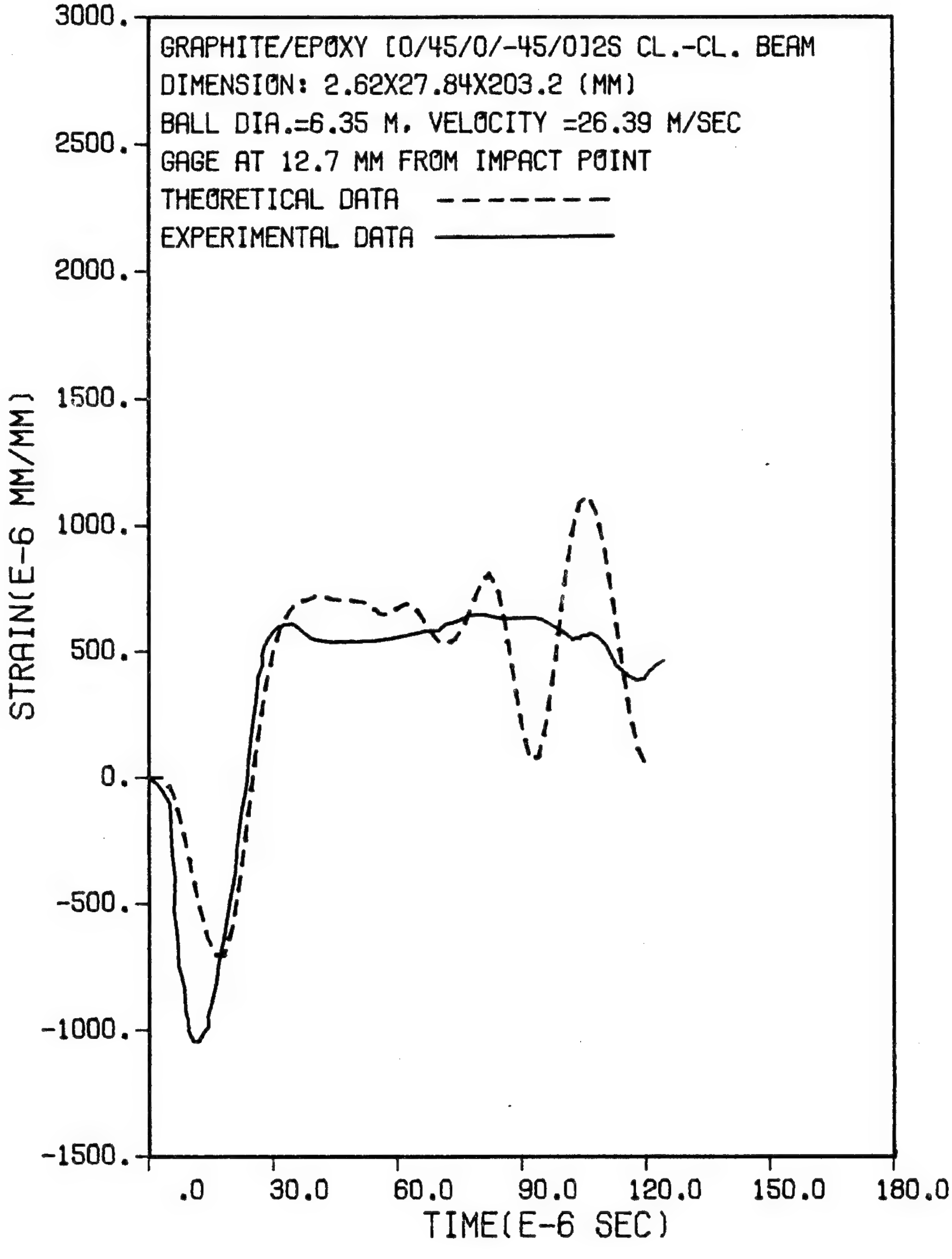


Fig. 22 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 12.7 mm from the impact point.

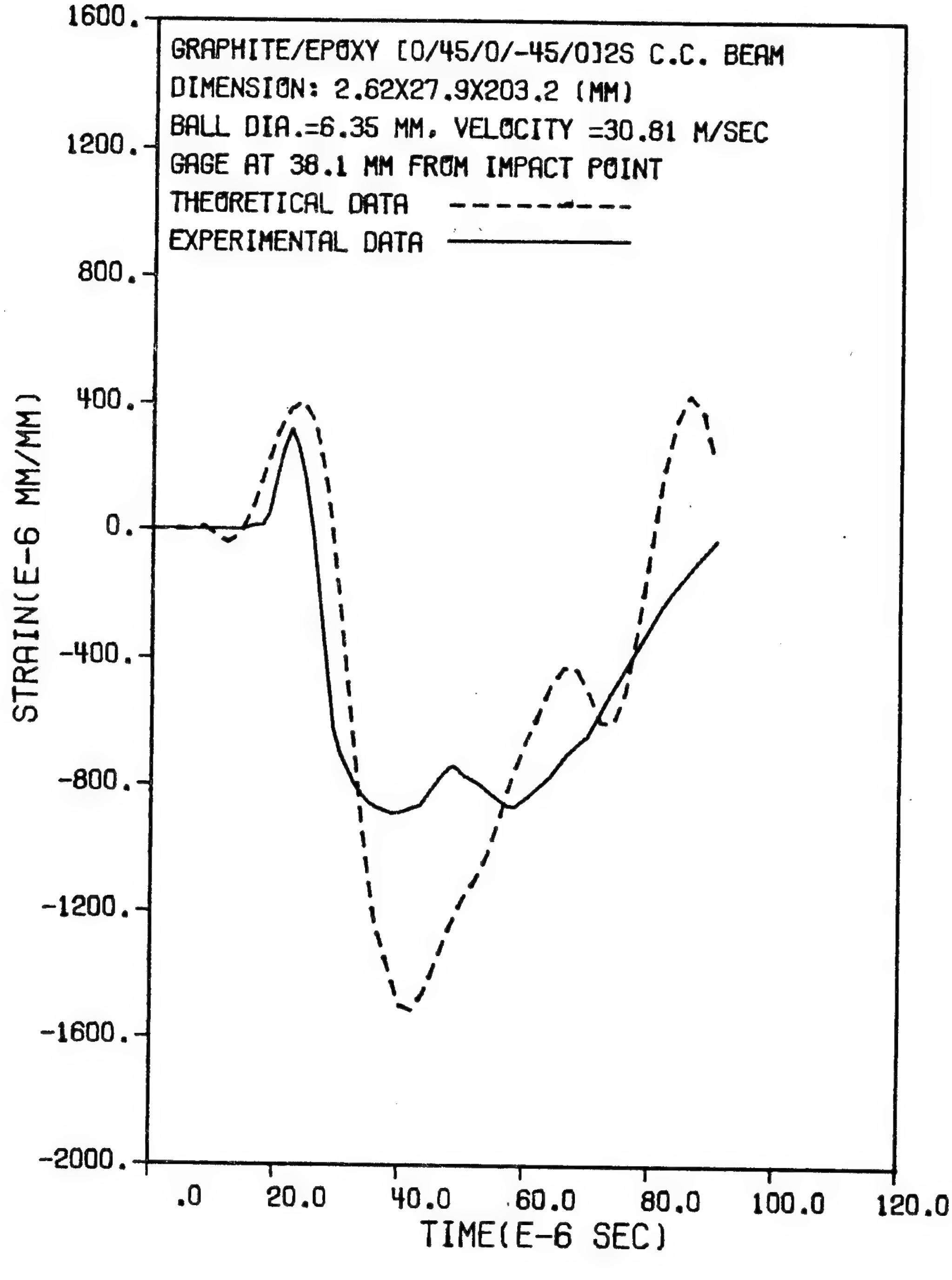


Fig. 23 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 38.1 mm from the impact point.

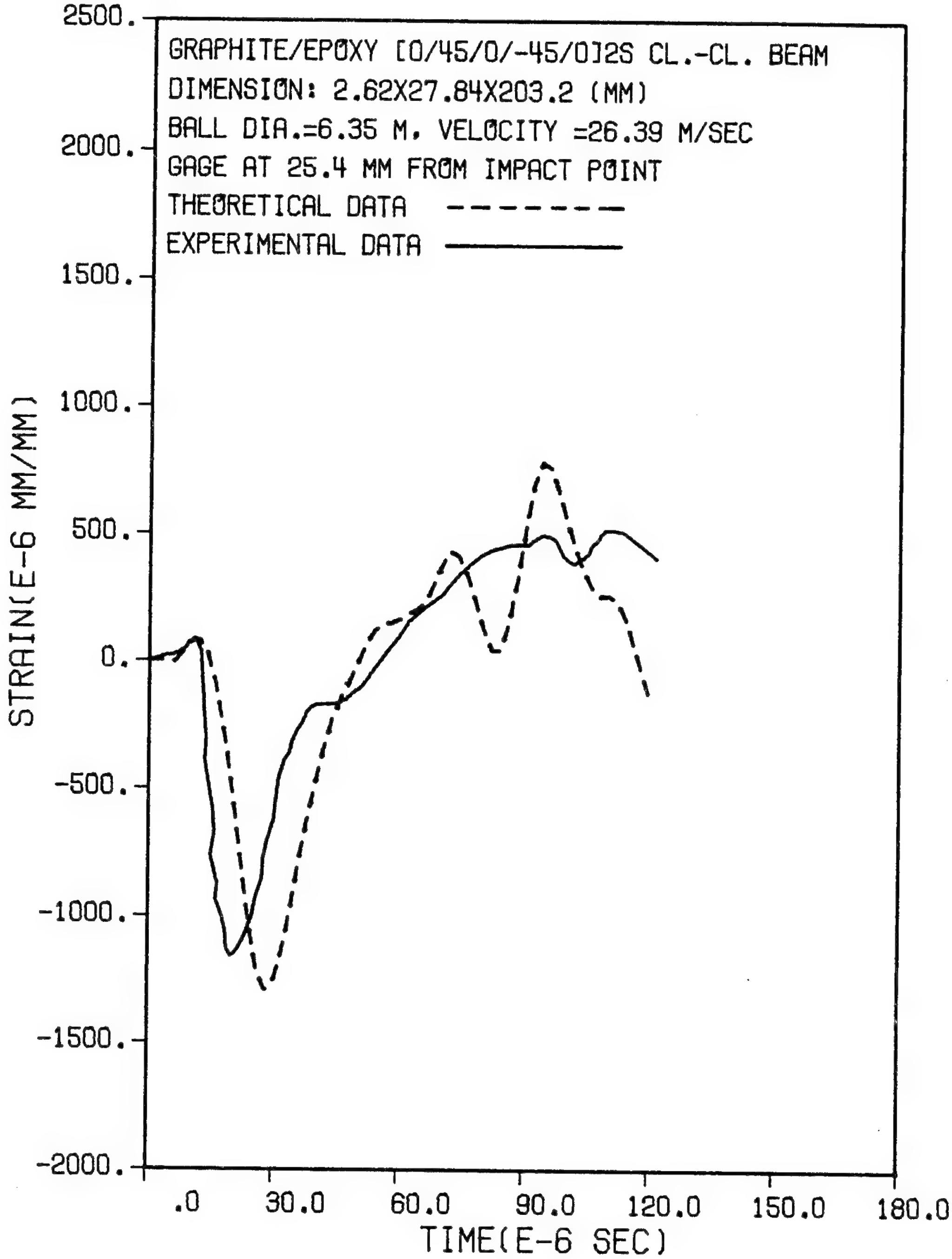


Fig. 24 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 25.4 mm from the impact point.

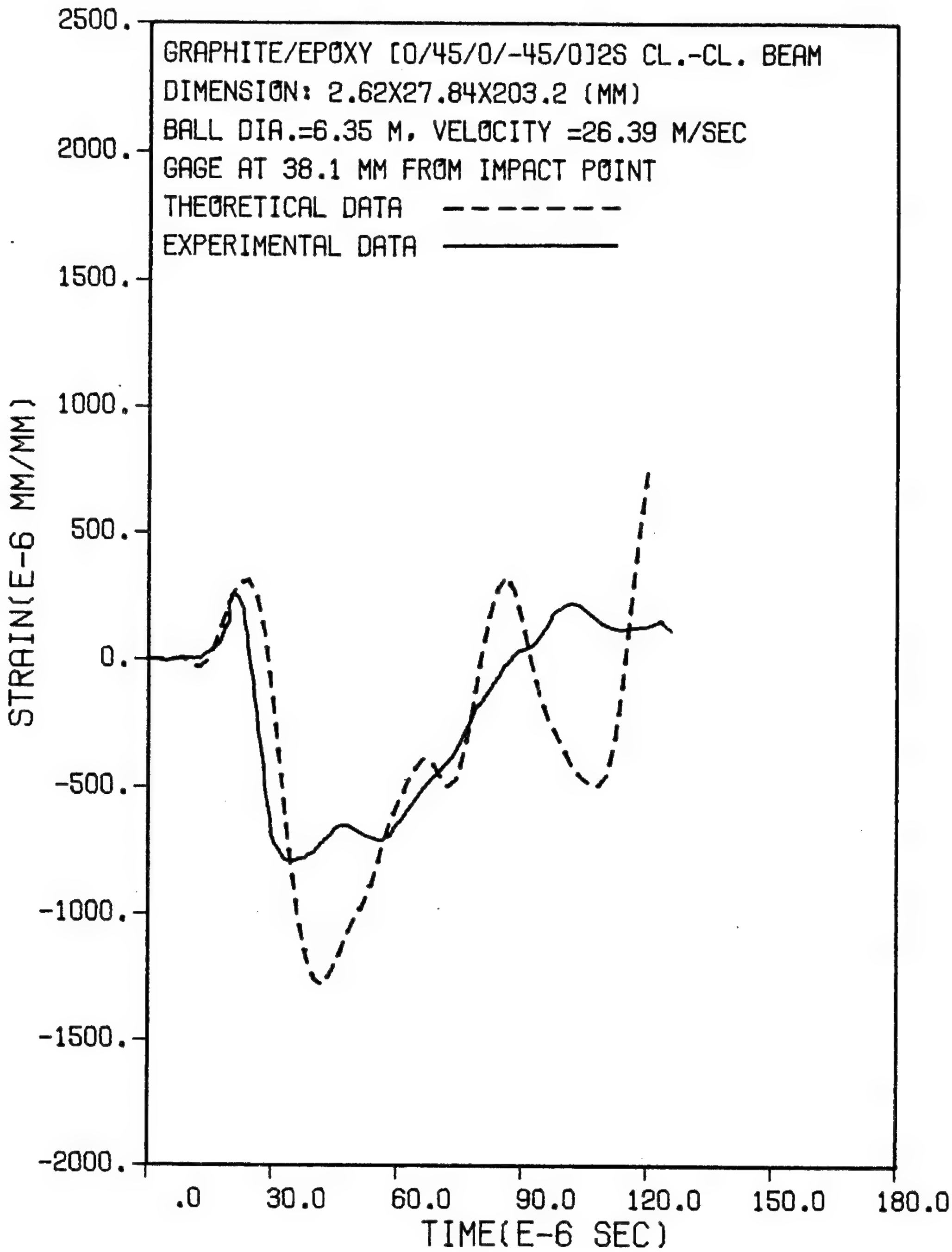


Fig. 25 Experimental and theoretical strain responses for a clamped-clamped $[0/45/0/-45/0]_{2s}$ beam at 38.1 mm from the impact point.

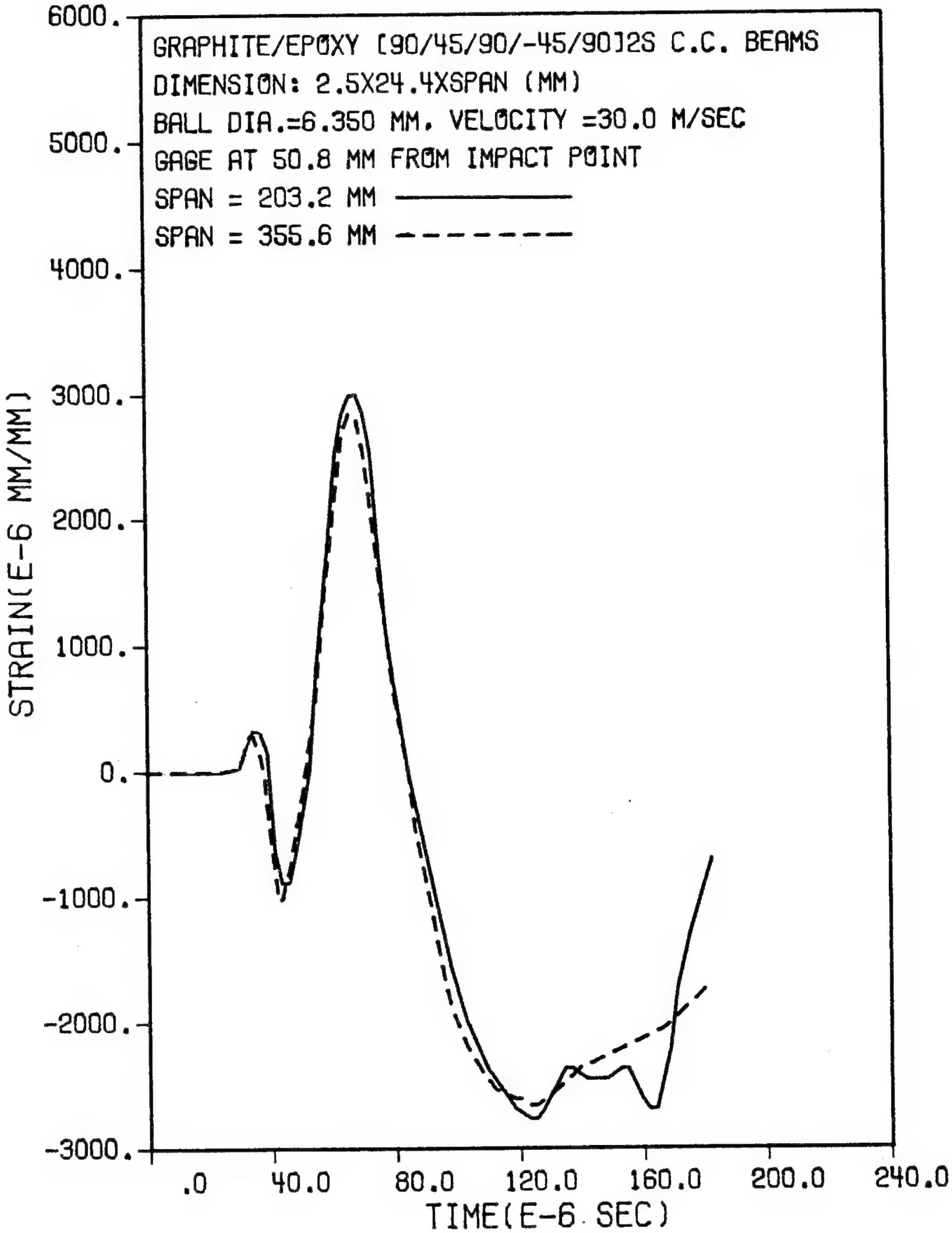


Fig. 26 Strain responses at 50.8 mm from the impact point for spans 203.2 mm and 355.6 mm.

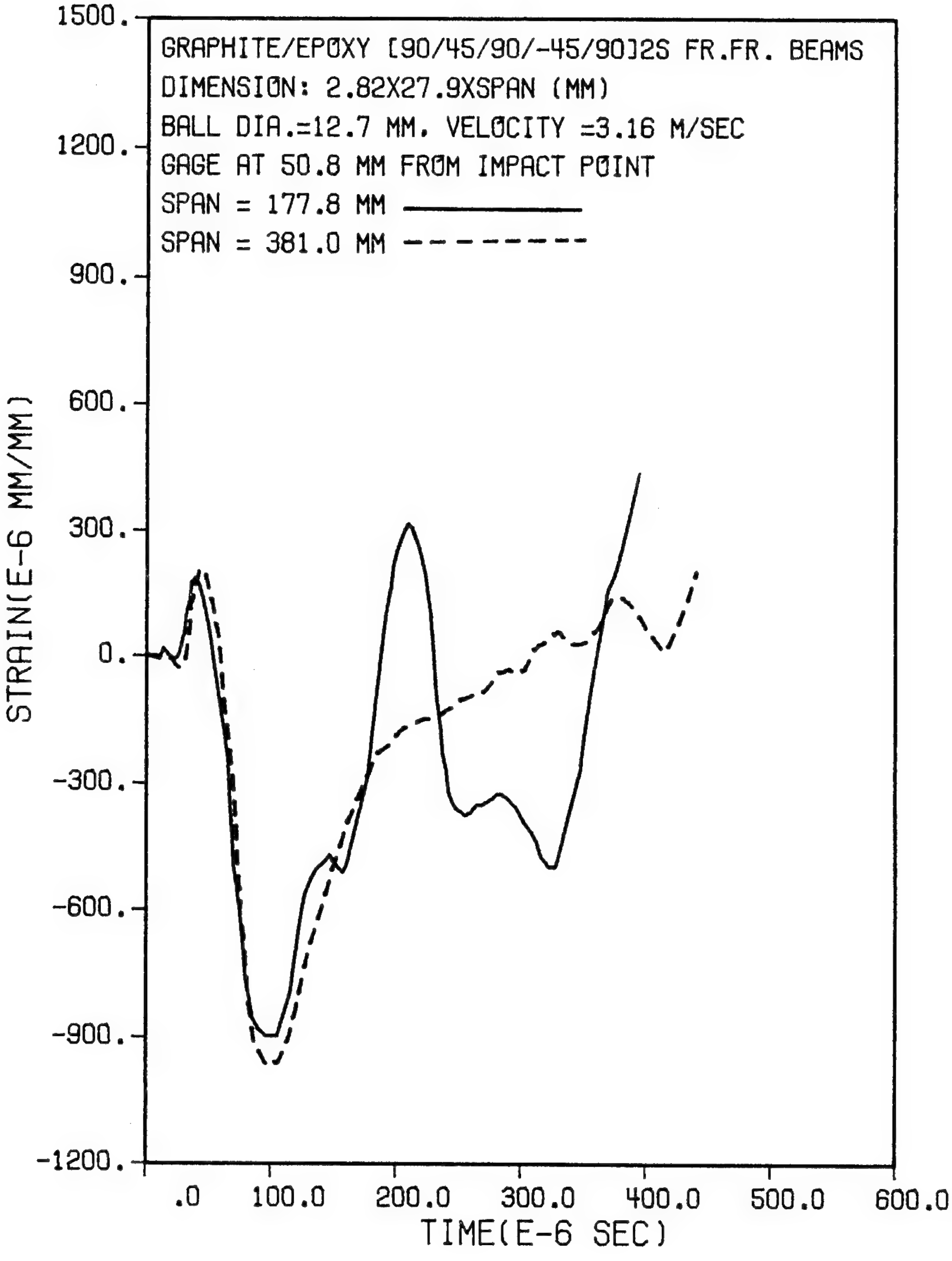


Fig. 27 Strain responses at 38.1 mm from the impact point for spans 177.8 mm and 381.0 mm.

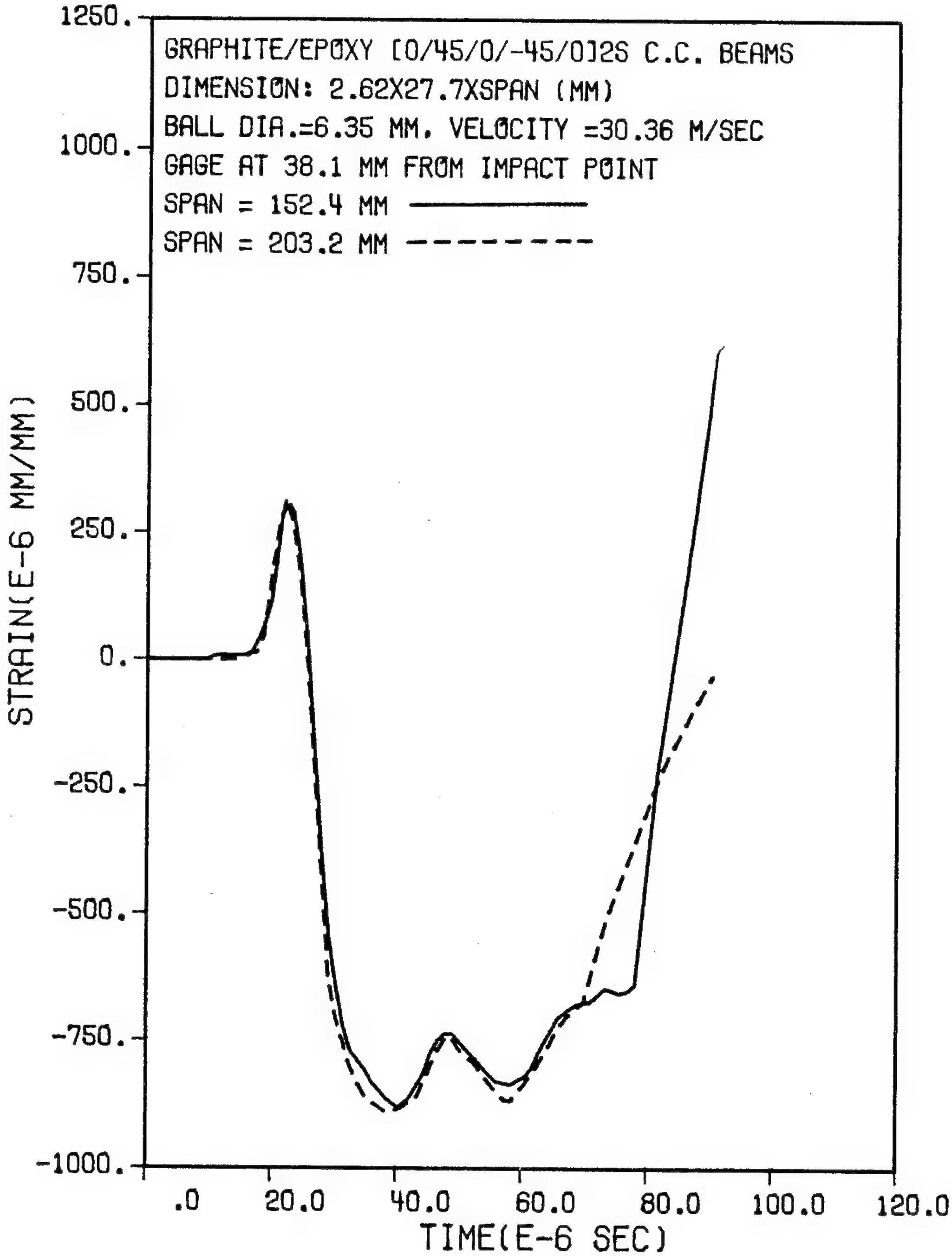


Fig. 28 Strain responses at 38.1 mm from the impact point for spans 152.4 mm and 203.2 mm.

TOPICAL REPORT

NSG-3185

DYNAMIC RESPONSES OF A GRAPHITE/EPOXY LAMINATES BEAM TO

IMPACT OF ELASTIC SPHERES

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